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ELF Communications System Ecological Monitoring Program: Upland Flora Studies – Final Report

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Technical Report D06212-4
Contract No. N00039-93-C-0001
October 1994

Prepared for:

Submarine Communications Project Office
Space and Naval Warfare Systems Command
Washington, D.C. 20363-5100

Submitted by:

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616-3799

"Statement A, Unlimited:"

IITRI

Printed in the United States of America

This report is available from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1994

3. REPORT TYPE AND DATES COVERED
Final Report, 1982-1994

4. TITLE AND SUBTITLE
ELF Communications System Ecological Monitoring Program:
Upland Flora Studies—Final Report

5. FUNDING NUMBERS
C: N00039-81-C-0357
N00039-84-C-0070
N00039-88-C-0065
N00039-93-C-0001

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616-3799

8. PERFORMING ORGANIZATION REPORT NUMBER
D06212-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Submarine Communications Project Office
Space and Naval Warfare Systems Command
Washington, D.C. 20363-5100

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified/Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The U.S. Navy has completed a program monitoring flora, fauna, and ecological relationships for possible effects from electromagnetic (EM) fields produced by its Extremely Low Frequency (ELF) Communications System. This report documents studies of upland flora conducted near the Navy's transmitting antenna in Michigan.

From 1982 through 1993 researchers from the Michigan Technological University (MTU) monitored tree, herb, and fungal species dominant in areas near (treatment) and far (control) from the ELF antenna. Above-ground parameters included the productivity, physiology, and phenology of trees, as well as the morphology and phenology of an herb. Below-ground, the important association between tree roots and fungi were monitored. Investigators also measured ambient weather conditions, soil nutrients, and EM field intensities. The MTU research team used analysis of variance and covariance to examine the data. When site-by-year interactions were significant, correlations and regressions were used to determine whether residuals were related to EM exposure.

Results suggest a possible subtle EM effect to the cambial and stemwood growth of some tree species but not to any other parameter. MTU investigators conclude no short-term, adverse effects on forest health from exposure to EM fields produced by the Naval Radio Transmitting Facility-Republic, Michigan.

(ABSTRACT PREPARED BY IIT RESEARCH INSTITUTE)

14. SUBJECT TERMS
bioelectromagnetic effects
ELF Communications System
ELF Ecological Monitoring Program
environmental studies
extremely low frequency fields
long-term ecological monitoring

15. NUMBER OF PAGES
236

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unclassified

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

FOREWORD

This report by researchers from Michigan Technological University (MTU) summarizes the results and conclusions of their study of upland flora. In this effort, MTU monitored tree, herb, and fungal species exposed to electromagnetic fields produced by the U.S. Navy's ELF Communications System in Michigan. The Space and Naval Warfare Systems Command (SPAWAR) funded this study through contracts N00039-81-C-0357, N00039-84-C-0070, N00039-88-C-0065, and N00039-93-C-0001 to IIT Research Institute (IITRI). IITRI, a not-for-profit organization, provided engineering support to MTU and managed their study through subcontract agreements.

MTU initiated their studies in late 1982. Their early efforts focused on selecting study sites, validating assumptions made in proposals, and characterizing critical study aspects. As these tasks were accomplished in 1984 and 1985, MTU then emphasized accumulating a data base through 1993. The MTU research team and IITRI evaluated each study variable for continued funding before contract renewals in 1984, 1988, and 1993. As a result, several originally proposed study elements were either expanded or discontinued in subsequent periods of performance.

Since its inception, scientific peers have reviewed the technical quality of this study on an annual basis. In similar fashion, a draft of this report has been reviewed by peers with experience in forestry, statistics, and electromagnetics. MTU authors have considered, and addressed, peer critiques prior to submitting a revised manuscript to IITRI. Except for added prefatory and title pages, MTU's manuscript is here issued by IITRI on behalf of SPAWAR without further changes or editing by IITRI or SPAWAR.

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IIT RESEARCH INSTITUTE

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ELF COMMUNICATIONS SYSTEM ECOLOGICAL MONITORING PROGRAM:

UPLAND FLORA STUDIES

FINAL REPORT

SUBCONTRACT NUMBER: D06205-93-001-LS

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EXECUTIVE SUMMARY

Background

In 1982, Michigan Technological University initiated research at the site of the Naval Radio Transmitting Facility - Republic, Michigan that would determine whether 76 Hz ELF electromagnetic (EM) fields generated by the facility cause changes in forest productivity or health. Studies initiated at analogous control, antenna right-of-way, and ground terminal sites have established a baseline of data that were used to compare various aspects of plant communities before and after the antenna became operational. In addition, comparisons were also made among both antenna sites and the control within a year for evaluating possible effects of ELF EM fields on forest ecosystems.

Studies of ecologically important tree, herb and fungal species have been the focus of ELF EM field studies at Michigan Tech. Existing stands of mixed hardwoods including northern red oak *(Quercus rubra)*, paper birch *(Betula papyrifera)*, red maple *(Acer rubrum)* and aspen *(Populus tremuloides* and *Populus grandidentata)* as well as red pine *(Pinus resinosa)* plantations established exclusively for this study, have been the subject of intense monitoring efforts with major emphases on measures of productivity such as height and diameter growth, production and nutrient content of foliage, and timing of phenological events. In addition, studies of the herb starflower (*Trientalis borealis* Raf.) and mycorrhizal fungi have been examined as potential indicators of ELF EM field effects. On-site measurements of ambient weather, site and EM field strength (magnetic flux density - mG) have been used in statistical analyses to evaluate potentially subtle ELF EM field effects on growth.

The ELF study database at Michigan Tech contains nine years of information, beginning in 1985 and continuing through 1993. Antenna testing began in 1986 (6 amps) and continued in 1987 (15 amps) and 1988 (75 amps) with operational levels (150 amps) being reached in 1989. The only exception to this occurred in May through June of the 1991 field season when the north-south antenna operated at full power while the east-west antenna was not used because of maintenance work. Prior to the start of these studies, 1.5 years were spent selecting, establishing and installing instruments on analogous plots. This Report examines the results observed through 1993.

Objectives

Our broad objective was to assess the impact of ELF fields on forest productivity and health. To accomplish this, more specific objectives were established to study various components of the forest ecosystem:

1) growth rates of established northern hardwood stands, individual hardwood trees and planted red pine,
2) timing of selected phenological events of trees, herbs, and mycorrhizal fungi,
3) numbers and kinds of indigenous mycorrhizae on red pine seedlings,
4) nutrient levels of hardwood and red pine foliage,
5) litter production in hardwood stands.

Insect and disease incidence is discussed in a related project on litter decomposition. Ultimately, the question of whether ELF EM fields measurably impact forest communities will be answered by testing various hypotheses (Table 1) using long-term plant and environmental measurements collected adjacent to and away from the antenna.

Table 1. Critical hypotheses tested to determine the environmental impacts of ELF EM fields on upland forest ecosystems.

I.	There is no difference in the magnitude or the pattern of seasonal diameter growth of hardwoods before and after the ELF antenna becomes activated.
II.	There is no difference in the magnitude of diameter growth of red pine seedlings before and after the ELF antenna becomes activated.
III.	There is no difference in the magnitude or rate of height growth of red pine seedlings before and after the ELF antenna becomes activated.
IV.	There is no difference in the rate of growth and phenological development of the herb, *Trientalis borealis* L., before and after the ELF antenna becomes activated.
V.	There is no difference in the number of different types of mycorrhizal root tips on red pine seedlings before and after the antenna becomes activated.
VI.	There is no difference in the total weight and nutrient concentrations of tree litter before and after the ELF antenna becomes activated.
VII.	There is no difference in the foliar nutrient concentrations of northern red oak trees or red pine seedlings before and after the ELF antenna becomes activated.

Project Design

Experimental Design

The study is best described as a repeated measures, split plot, experimental design. Each site (control, antenna, and ground) is subjected to a certain level of ELF field exposure and is subdivided into two subunits (hardwood stands and red pine plantations). These stand types comprise the treatments for the second level of the design. Each stand type is replicated three times on a site (where sites represent different levels of ELF field exposure) to control variation in non-treatment factors that may affect growth or health such as soil, stand conditions and background and treatment EM field levels. It is necessary to account for time in the experimental design since, for some response variables, successive measurements are made on the same plots and individual trees without re-randomization. The time component is the number of years that an experiment is conducted for baseline-to-treatment comparisons, and the number of sampling periods in one season for year-to-year comparisons

All sites follow this design except at the ground where there was no hardwood stand because buffer strips required to minimize 'edge effects' on plot borders would have resulted in the stands being too distant from the antenna ground cable for significant exposure to ELF fields.

Testing for ELF EM Field Effects

At the outset of the project, it was known that the EM fields associated with the ELF system would be different at the antenna and ground locations. IITRI has measured 76 Hz electric field intensities at the antenna, ground, and control sites since 1986 when antenna testing began and background 60 Hz field levels were measured at all sites in 1985. Three types of EM fields are measured: magnetic flux density (mG), longitudinal (earth) electric (mV/m), and transverse (air) electric (V/m).

From IITRI measurements of field strength at the sites, it is apparent that electric field intensities are affected by vegetative and soil factors. Also, treatment levels have not been uniform over time because of the various testing phases prior to antenna operation. Since the antenna was activated for low level testing throughout the growing seasons of 1986 - 1988 and full power operation in 1989, hypothesis testing examines differences in response variables between these and previous years, and differences between control, antenna and ground sites in 1987 through 1992 (or 1993 depending on the variable).

The most extensive comparisons are for yearly and site-within-year differences. For all hypotheses, ambient and other variables are used to account for site and year differences. Comparisons between pre- and post-operational years are made, as are comparisons of relationships between sites after antenna activation, to determine whether antenna operation has had a detectable effect on the response variables. For those elements where analysis of covariance is used, we test to insure that covariates are statistically independent of the EM fields and then examine whether fields explain differences for a particular response variable. If differences are apparent in the modeling effort, correlation and regression is used to determine whether residuals from these analyses are related to ELF fields.

Measures of Ambient Growing Conditions

Our experimental design directly controls field error through replications at sites. Indirect, or statistical control, also increases precision and removes potential sources of bias through the use of modeling and covariate analysis. Climate and soil nutrient contents at the three study sites (control, ground and antenna) were measured to monitor site and year variation in these important environmental factors during the study period. Variation of these factors among sites during the study were also compared to determine if they were statistically independent of antenna operation and to quantify any changes in these environmental variables related to ELF EM induced changes in community structure or productivity. Climate and soil nutrients which were independent of antenna operation were then considered available for use in models and statistical analyses used to evaluate ELF EM effects on other forest ecosystem processes and attributes. ANOVA tests were used to indicate whether changes in climate and soil nutrients among sites during the study were greater than the natural spatial and temporal variation observed at the study sites. Multiple range tests were then used to determine whether these changes were consistent with the operational patterns of the antenna during the study. Finally Pearson's product correlation coefficients were used to determine if these changes were correlated to EM field strengths within the test sites.

For the red pine plantations, differences in air temperature, soil temperature, soil moisture, and relative humidity for at least one of the site comparisons were found to change after full power antenna operation. However, these changes were primarily related to inherent site differences in height growth and number of trees which survived the initial planting stress rather than EM field exposure. For the hardwoods, only differences in soil temperature at a depth of 10cm between the sites was significantly correlated ($p \leq 0.05$) with 76 Hz magnetic fields. This climatic variable was the only variable not found to be independent of antenna operation. Although we could not conclude that soil temperature at a depth of 10cm was independent of antenna operation, there was no indication that

changes in temperature within the hardwood stands were due to any ELF-induced alteration of the communities at the antenna site.

Results And Discussion

The critical hypotheses for the project (Table 1) will serve as the framework for summarizing our results.

- **Hypotheses:**

  I. There is no difference in the magnitude or the pattern of seasonal diameter growth of hardwoods before and after the ELF antenna becomes activated.

  II. There is no difference in the magnitude of diameter growth of red pine before and after the ELF antenna becomes activated.

  III. There is no difference in the magnitude or rate of height growth of red pine before and after the ELF antenna becomes activated.

The impacts of ELF electromagnetic fields on tree productivity were examined in both the hardwood stands and the red pine plantations. Cambial development, as indicated by weekly diameter growth at 1.37m from the ground line, was the primary response variable examined in the hardwood stands. Weekly height growth was the primary response variable in the red pine plantations. In addition, leaf water potential was also examined in the red pine plantations. Seasonal air temperature degree days, Mid-summer mineral soil potassium concentration, and soil water-holding capacity were utilized to account for inherent differences in growing conditions between sites and among years for hardwood diameter growth. Seasonal air temperature degree days and soil water potential were utilized to account for between site and among year differences in red pine height growth.

Mapping tree locations and monitoring ELF EM fields at selected locations across the study sites allowed the determination of EM exposure levels for each tree within the hardwood stands and the red pine plantations. Annual magnetic flux density level was the EM variable used to represent the entire spectrum of EM exposure received by individual trees.

Equations developed during pre-exposure years were used to estimate tree productivity based on annual growing conditions. Differences between the predicted and observed growth rates were examined in relation to the magnetic flux density exposures to determine if EM exposure might be influencing tree growth. Based on these analyses, there are significant ($p<0.05$) relationships between diameter growth and magnetic flux density exposure levels for aspen (*Populus tremuloides* and *P. grandidentata*) and red maple (*Acer rubrum*), and between red pine annual height growth and magnetic flux density level. There is

no evidence ($p=0.05$) of an impact of EM fields on red pine diameter growth or the seasonal patterns of hardwood diameter growth or red pine height growth. In related work, there is no evidence ($p=0.05$) of an impact of antenna operation on red pine leaf water potential.

- **Hypothesis IV. There is no difference in the rate of growth and phenological development of the herb, *Trientalis borealis* L., before and after the ELF antenna becomes activated.**

Phenological events, or the timing of certain morphological processes, are important phytometers of plants under stress. In this portion of the study, a small herbaceous plant, starflower (*Trientalis borealis* Raf.), was used as an indicator of ecosystem responses to ELF EM fields. Both phenological and morphological characteristics were monitored from 1985 to 1992. Phenological measurements included stem elongation, budbreak, leaf expansion, flowering, fruiting and leaf senescence. Morphological measurements included leaf area, leaf length and width, stem length, number of buds, number of leaves, number of flowers, and number of fruit.

Phenology results indicate significant site by year interactions ($p < 0.01$) in Julian dates of initial leafout and budbreak. These differences were attributed to our initiation of sampling in the spring and not to the ELF fields. Other observed differences were in the initiation of flowering and fruiting events. Before the antenna was operational, initiation of flowering and fruiting events on both the antenna and control sites began when the previous event (e.g., bud break and flowering, respectively) was at its maximum. However, in 1992, initiation of flowering and fruiting on the antenna site occurred before this peak (maximum). Reasons for these changes are unclear since initiations of flowering and fruiting in 1990 and 1991 on this site were similar to patterns found in 1985-1989. Climatic conditions in May of 1991 (higher temperatures and precipitation amounts) were, however, similar to climatic conditions in 1985-1989.

Morphology results indicated significantly lower ($p < 0.05$) numbers of plants with buds, flowers, and fruits on the antenna site in 1986, 1987, and 1988 than on the control site for those years. No significant differences between the antenna site and control site ($p = 0.05$) in the number of plants with flowers and fruits were observed after 1988. Significant variation in stem lengths, leaf lengths and widths, and leaf areas between the antenna and the control sites were explained using microsite basal areas, soil temperature degree days running total at 10 cm, maximum solar radiation, and total precipitation. These covariates also explained significant variations in leaf area among site-by-year interactions; however, significant ($p < 0.05$) site by year differences for stem lengths, leaf lengths, and leaf widths were detected.

When individual means for stem length, leaf length, and leaf area were statistically compared, no discernible pattern due to ELF effects was observed.

Mean values for all variables decreased on both the Antenna and the Control site over the eight years of this study. Handling the plants when measuring was suggested as a possible cause for these decreases; however, a separate study indicated that handling did not significantly affect the above-mentioned variables. Our conclusion from this study is ELF fields have not significantly affected starflower phenological processes or morphological characteristics.

- **Hypothesis V. There is no difference in the number of different types of mycorrhizal root tips on red pine seedlings before and after the antenna becomes activated.**

Mycorrhizae of plantation red pine seedlings were used as biological indicators to reflect perturbations that might be caused by ELF EM fields. Mycorrhizae are the association of fungi and individual plant roots, and are a major component of forested ecosystems. These fungi are obligate symbionts and are directly dependent on a plant's physiology for their health. Therefore, they could indicate decreases in plant health due to ELF EM fields. Mycorrhizal numbers per gram of dry root by morphological type were measured on 270 planted red pine (*Pinus resinosa*) seedlings per year from 1985 to 1993.

If ELF EM fields affect mycorrhizal numbers, the most important source of variation attributable to these effects would be determined in site-by-year interactions. Numbers of mycorrhizae during ELF operational years on the antenna and/or ground site(s) would be significantly different than the numbers on the control site or from prior years information. Using analysis of variance results indicated that mycorrhizal numbers were not significantly different ($p < 0.05$) among sites and among site-by-year interactions. Using analysis of covariance (two variables: *i*) total precipitation, and *ii*) days with precipitation >0.10 cm) differences among sites and site-by-year interactions were not detected. These results indicate that mycorrhizal symbiosis between tree roots and fungi have not been significantly affected by ELF fields.

- **Hypotheses VI. There is no difference in the total weight and nutrient concentrations of tree litter before and after the ELF antenna becomes activated.**

Litter fall indicates foliar production and is important for the transfer of nutrients and energy within a vegetative community. This makes litter fall a good indicator of possible ELF field effects on forest ecosystems. Litter samples were gathered at frequent intervals during the growing season at both the antenna and control hardwood sites. This provided an estimate of change in canopy production prior to and during ELF antenna operation. Litter was collected from five 1m^2 traps located in each of three permanent measurement plots established in the hardwood stands. Samples were separated into leaves, wood, and miscellaneous components, and a subsample of leaf litter was further separated

by tree species. All litter samples were weighed and analyzed for N, P, K, Ca, and Mg contents.

Annual total litter production amounts varied considerably between the antenna site and the control. Analysis of covariance using stand and environmental variables as covariates was used to reduce litter production variability between the two sites, and increase the possibility of detecting ELF effects using eight years of litter fall data. Soil and air temperatures generally showed the highest correlations with litter production. When these variables were used in the analyses of covariance, there was no detectable effect of ELF EM fields on litter production.

Average nutrient concentrations of the various litter components and for the leaves of individual tree species also showed considerable variability between the antenna and the control sites. Analysis of covariance was again used to try and separate possible ELF effects from site and ambient factors. These results showed that significant litter nutrient concentration differences existed between sites prior to antenna construction, and were not affected by the ELF antenna operation.

- **Hypothesis VII. There is no difference in the foliar nutrient concentrations of northern red oak trees or red pine seedlings before and after the ELF antenna becomes activated.**

Leaf samples were taken during the growing season from: 1) various sized northern red oak trees (15 cm, 21 cm, and 32 cm diameter) growing on both the antenna and control sites and 2) red pine seedlings planted on all three sites. The samples were used to monitor possible ELF effects on leaf weight and nutrient accumulation. Nutrient translocation from red oak leaves to branches prior to leaf fall was also determined.

Nutrient concentrations in red oak and red pine foliage during the growing season showed considerable variability between the ELF test sites and the control, but these generally reflected the nutrient status of the sites before antenna transmissions began. Similar results were found for leaf weight. Red pine foliar concentrations were not significantly correlated with 76 Hz magnetic flux densities. Differences in red oak and red pine foliage nutrient concentrations and weight among the three study sites were not related to operation of the ELF antenna.

Perspective

A suite of potentially sensitive biotic indicators was investigated in a long-term study to determine whether 76 Hz ELF EM fields generated by the Naval Radio Transmitting Facility - Republic, MI cause changes in forest productivity or health

of northern hardwood and pine forests. The major aboveground ecological measures included tree productivity, phenology, and nutrition, along with morphology and phenology of the herb, starflower. Belowground measures concentrated on numbers and morphology of red pine mycorrhizae. The field setting for the research presented challenges in separating possibly subtle ELF field effects from natural variability in the forested ecosystems. These were met through the measurement and analysis of soil and climate variables, and the experimental design which together resulted in reasonable detection limits for the variables under consideration.

Forest Production: For most variables, four years of measurements were taken during full power antenna operation. During this time, aspen and red maple diameter growth and red pine height growth were moderately accelerated for trees exposed to ELF magnetic flux density levels in the very narrow range of 1-7 mG. However, red pine diameter growth and the seasonal patterns of both hardwood diameter growth and red pine height growth showed no response to ELF EM field exposure. While these findings are inconsistent in the sense that only some growth measures show a response to ELF EM fields, the results do suggest a subtle perturbation which has not adversely affected forest production.

Forest Health: While stemwood production shows some stimulation, litter production and nutrient concentration, red oak and red pine foliar nutrient levels, starflower phenology and morphology, and mycorrhizae numbers and morphology were not affected by ELF EM fields at detectable levels. This study shows that there are no short-term effects of ELF EM fields on forest health. The future effect of stimulated growth or long-term ELF EM exposure on forest health is beyond the scope of this research.

CHAPTER 1

SITE SELECTION, PLOT ESTABLISHMENT, AND EXPERIMENTAL DESIGN

Peter J. Cattelino, Glenn D. Mroz, David D. Reed, Martin F. Jurgensen, Elizabeth A. Jones, Margaret R. Gale, and Hal O. Liechty

ABSTRACT

Three study sites were located in second growth hardwood stands in the central Upper Peninsula of Michigan to assess the potential effects of the U.S. Navy's 76 Hz, ELF communication antenna on forest growth and productivity. Study areas were chosen to be as similar as possible in order to minimize the natural variation in the measured response variables. Initial identification of sites was aided by aerial photography and Michigan Department of Natural Resources forest inventory data and personnel. Potential sites were screened by obtaining detailed field measurements which were analyzed to determine suitability as study sites. Test sites were located along an overhead portion of the antenna (antenna site) and along a terminal ground wire (ground site) while a control site was located approximately 50 km from the test sites. The control was located such that background 60 Hz electromagnetic fields would not differ by more than one order of magnitude from the test sites, and 76 Hz fields generated by the ELF system would be at least one order of magnitude lower than at the test sites. Analysis of field data showed strong similarity among the sites in biological and environmental parameters. All study sites are in the same regional ecosystem and have similar vegetation and climate. Vegetation on each site is classified in the *Acer-Quercus-Vaccinium* habitat type and several similarity indices computed for the overstory showed similarity in species composition and biomass to be greater than 80 percent. Although morphologically similar, soil at the antenna site was classified differently from the ground and control sites. The differences observed between sites are minor, and at the time the sites were selected, they were expected to respond similarly to any environmental influence such as ELF fields. While the sites were carefully chosen, the experimental design, which is best described as a repeated measures split plot, was used to separate possibly subtle ELF field effects on response variables from the existing natural variability caused by soil, stand, and climatic factors over time.

INTRODUCTION

Detection of potentially subtle ELF electromagnetic field effects on forest productivity and health requires the careful matching of study sites to reduce the natural variability in measured parameters that exist among the sites. The variability in plant growth and growth processes within the ELF system area must first be related to naturally occurring variation in environmental characteristics among the study sites before any change in the response variables can be attributed to ELF fields. This can be partially

accomplished by careful selection of test and control sites, taking into account all appropriate site characteristics that influence forest vegetation. The study design required test sites to be located along an overhead portion of the antenna (antenna site), along a terminal ground wire (ground site) and at a control site. The control site was to be located at a distance from the ELF antenna where background 60 Hz electromagnetic (EM) fields would not differ by more than one order of magnitude from the antenna site but 76 Hz fields generated by the ELF system would be one order of magnitude greater than at the control and test sites. Permanent measurement plots at the antenna and control sites were established in existing second growth northern hardwood stands and in newly planted red pine (*Pinus resinosa*, Ait.) plantations. Only red pine plantation plots were established at the ground site. The study sites were established prior to the operation of the ELF antenna in order to obtain baseline data prior to ELF electromagnetic (EM) field exposure. Soil characteristics, microclimate, site history, landform, and the vegetative community were carefully evaluated to insure as much similarity between test and control sites as possible. A rigorous repeated measures split plot statistical design was used to separate possibly subtle ELF field effects from existing natural variability in site and climatic factors.

SITE SCREENING

Approximately 20 potential test and control sites were identified through use of the Michigan Department of Natural Resources (DNR) Operations Inventory and Continuous Forest Inventory (CFI), aerial photography of the proposed ELF system area, and in consultation with DNR personnel. The goal of this effort was to identify three sites (2 test sites and a control site) which had similar physical site characteristics, mix of hardwood tree species, understory vegetation, and acidic soils with sandy to sandy loam surface horizon textures. Each potential study site was visited and preliminary observations recorded. Many of the sites were eliminated as study candidates because they did not meet the selection criteria listed above. Sites meeting the preliminary requirements were revisited and detailed field measurements taken to determine their suitability as study sites (Table 1.1).

Electromagnetic Field Criteria

In addition to selecting sites with similar biological and physical parameters, the study design required similar background 60 Hz EM exposure between test and control sites, but dissimilar ELF 76 Hz exposure. To aid in locating study sites that met these specifications, criteria were developed for EM exposure levels between the test and control sites (Appendix A).

Table 1.1. **Measurements used for describing potential ELF study sites.**

Trees	Ground Flora
Species Composition	Composition
Basal Area	Frequency
Diameter Distribution	Coverage
Site Index	
Soil Morphology	**Site**
Horizon Identification	Slope
Horizon Thickness	Aspect
Texture	Landform
Drainage	Habitat type
Presence of Earthworms	
Rock Abundance	

Measurements of background 60 Hz EM fields were made at fixed points at each study site in May and August, 1984 by IITRI personnel in order to evaluate tentative study sites using the EM exposure criteria. The magnetic flux density and electric field intensities in air and in the earth were measured using directional field probes designed and calibrated by IITRI (Brosh *et al.* 1985). Computer-generated estimates of EM 76 Hz fields were developed using anticipated operational power levels and were provided by IITRI in the form of contour map overlays and curves of electric and magnetic field intensities as a function of the distance from the antenna. This information was then used to identify potential sites that met the EM field exposure criteria.

SITE SELECTION AND DESCRIPTION

Selection of Test Sites

Because the site selection process began prior to the construction of the ELF system, it was necessary to know the precise configuration and location of the antenna right-of-way before the ground site and the antenna site could be established. Selection of the ground site was given highest priority because this portion of the ELF system represented the most limited land area available for site selection. Following an update on the location of the ELF system ground terminals, potential sites identified through initial screening were reviewed again to determine if any of these sites were located along the ELF ground terminals. As a result, a site was identified along ground terminal #5 on the western end of the southern east-west leg of the antenna in southern Marquette County which met the selection criteria. In March 1993, this site was selected as the ground site. Once the ground site was chosen, selection of the antenna and control sites depended on matching the biological and physical conditions found at the ground study site. Based on review of the detailed field surveys of

potential study sites, the antenna site was selected in April 1983 along the southern east-west leg of the ELF antenna system approximately 1 km from the ground site.

Selection of the Control Site

After further review of field data obtained from potential study sites, a control site was selected in Iron County south of Crystal Falls in April 1983. However, in November 1983, we were informed by IITRI that the control site failed to meet ELF EM site selection criteria for 60 Hz fields in the earth. Data indicated that these fields differed by more than one order of magnitude from the relatively low 60 Hz fields measured at the antenna and ground sites. Subsequently, a new control site needed to be located closer to a known source of 60 Hz fields to reduce the difference in field intensity between sites in order to meet the established criteria. In the spring of 1984, a new control site was located approximately 2 km east of the original site. Results of EM measurements of the 60 Hz field in the earth at the new site indicated that the two measurement points closest to a nearby 69 kV transmission line slightly exceeded the established criteria; all other measurement points at the site were acceptable. All measurement points were acceptable for the 60 Hz EM field in air and the 60 Hz magnetic flux density. Thus, across this site, a gradient of about 10:1 exists in the 60 Hz field in the earth. The site was then classified as conditionally acceptable (Brosh, *et al.* 1985). The criteria were met on all measurement points for each of the 76 Hz ELF fields which were estimated based on analysis of the proposed operational conditions of the antenna elements and the distance from the antenna to the measurement points.

Physical Site Description

Maps of actual site locations and plot configurations are provided in Appendix B. The ground, antenna, and control sites are all in the same regional ecosystem and have similar geology and climate (Albert *et al.* 1986). The sites have short growing seasons (87 days) and are subject to climatic influences of the Great Lakes. Physical descriptions of each site show minor variation in slope, aspect, and elevation among sites (Table 1.2).

Table 1.2. Physical description of study sites.

	Ground	Antenna	Control
Location	NW¼,NE¼, Sec. 28, T45N R29W	NE¼,NE¼, Sec. 28, T45N R29W	SW¼,SW¼, Sec. 3, T41N R32W
Percent Slope	0-30%	7-15%	0-15%
Aspect Range	NW	W-NW	NW
Slope Position	Level to Crest of ridge	Crest of slope to mid-slope	Crest of slope to mid-slope
Elevation	445 M	454 M	420 M
Habitat Type	Acer-Quercus-Vaccinum	Acer-Quercus-Vaccinum	Acer-Quercus-Vaccinum
Soil Classification	Alphic Haplorthod	Entic Haplorthod	Alphic Haplorthod

Understory Vegetation Classification

Similarity in understory vegetation was evaluated by classifying each site by habitat type (Coffman *et al.* 1983). Vegetation at each site was surveyed and then classified by the habitat type criteria; all three sites were classified as the *Acer-Quercus-Vaccinium* habitat type. Vegetation characteristics of this habitat type are shown in Table 1.3.

Table 1.3 Major overstory and understory species within the Acer-Quercus-Vaccinium habitat type (Coffman *et al.* 1983).

Overstory	Understory
Red maple (*Acer rubrum*)	Low sweet blueberry (*Vaccinium membranaceum)*
Northern red oak (*Quercus rubra*)	Bracken fern (*Pteridium aquilinum*)
Paper birch (*Betula papyrifera*)	Canada blueberry (*Vaccinium myrtilloides)*
Bigtooth aspen (*Populus granidentata*)	Large leaf aster (*Aster macrophyllus*)
Quaking aspen (*Populus tremuloides*)	Beaked hazelnut (*Corulus cornuta*)

The *Acer-Quercus-Vaccinium* habitat type is most common on sandy soils with moderate horizon development. Also red maple and northern red oak dominate the late successional stages of this type, indicating a high probability of stable species composition accommodating the long-term ELF studies (Coffman *et al.* 1983).

Overstory Characteristics

Tree Inventory

All trees in the hardwood stands with diameters greater than 10 cm were inventoried at the antenna and control sites. This diameter limit was chosen because trees greater than 10 cm are usually dominant or co-dominant in these stands and, since study trees were to be fitted with dendrometer bands, trees smaller than 10 cm would not allow the springs on the dendrometer bands to exert enough tension to insure a snug fit against the tree (Cattelino *et al.* 1986). Tree species, total height, and DBH were recorded for each tree; basal area, stems per hectare, site index, and age were determined for each site (Table 1.4).

A Kolmogorov-Smirnov two-sample test was used to test the hypothesis of similar diameter distributions for each species at the antenna and control sites. There were no differences ($p>0.10$) in diameter distributions for bigtooth aspen, northern red oak, and paper birch. However, the diameter distribution for red maple was found to be different ($p<0.005$) with a greater proportion of large-diameter trees at the antenna site (Mroz *et al.* 1985).

Table 1.4. Summary of hardwood stand information for the antenna and control sites in 1985.

Species	Average DBH (cm)	Average Total Ht. (m)	Average Basal Area (m^2/ha)	Stems Per Hectare	Site Index	Age (yrs)
ANTENNA						
Northern Red Oak	22.45	17.62	6.57	143	68	46
Paper Birch	20.23	19.62	0.86	25	66	54
Big Tooth Aspen	25.01	20.27	2.43	48	68	49
Red Maple	15.09	16.43	7.78	410	56	41
CONTROL						
Northern Red Oak	20.55	22.24	20.00	556	72	51
Paper Birch	16.47	20.63	2.92	127	60	53
Big Tooth Aspen	22.96	23.51	3.33	79	65	54
Red Maple	11.97	16.31	0.52	48	58	44

While all species of interest are present at each site, they differ in numbers of individuals present. For example, the number of northern red oak trees is larger at the control site while the number of red maple trees is larger at the antenna site. However, the inventory data indicated that there were adequate numbers of similar sized trees of each species at each site to adequately compare growth between sites.

Species Similarity Indices

Several similarity indices were used with the tree inventory data to estimate similarities in species composition between the antenna and control sites (Mueller-Dombois and Ellenberg, 1974). The ground site was not included in the these tests since there were no hardwood plots established there. The presence/absence of tree species was quantified using the Jaccard and Sorenson similarity indices. Sorenson's index differs from Jaccard's in that it gives greater weight to the species that are common to both test sites than to those that are unique to either site. Site selection criteria for this study were based on similarities between sites and not uniqueness, thus the Sorenson index was given greater emphasis in site selection.

Jaccard: $I_J = \frac{C\,x\,100}{All\ Species}$ Sorenson: $I_S = \frac{C}{1/2(A+B)}$

Where: C =# species common to each site
A =# species on site A
B = # species on site B

The similarity of the two sites is not only a function of the common and unique species, but also of the amount of each species present. Similarity between the sites based on total biomass of each species was quantified by the Ellenberg similarity index:

$$\text{Ellenberg: } I_E = \frac{C/2}{A+B+C/2}$$

Where: C = total biomass of common species
A = biomass of species unique to site A
B = biomass of species unique to site B

Because of the quantitative differences in abundance of each species between sites, a polar ordination technique (Bray and Curtis, 1957) was also used to test similarity based on total biomass and number of stems per site. Results of these tests show strong similarity between the antenna and control site with Jaccard, Sorenson, and Ellenberg indices of 80%, 89%, and 98%, respectively. However, the Bray and Curtis analysis showed only 40% similarity in the amount of stems per species and 66% similarity in amount of total biomass per species.

Soil Characteristics

Soil Classification

Soil physical and chemical properties were described at each study site in 1983 and 1984. The soils on the three sites, although morphologically similar, are classified differently (Table 1.5), (USDA Soil Conservation Service, 1975).

Table 1.5. Soil Classification of the ELF Study Sites.

Ground	Alfic Haplorthod, sandy, mixed, frigid
Antenna	Entic Haplorthod, sandy, mixed, frigid
Control	Alfic Haplorthod, sandy, mixed, frigid

Field descriptions of these soils are presented in Appendix C. Soils at each site are sandy loam in texture and are found on glacial till and outwashes. Soil horizon designations and depths are similar for the surface soil (top 50 cm) at all sites. Subsurface horizons (greater than 50 cm depth) show greater variation in horizon designation, but are similar to the surface horizons in texture with the exception of the E' horizon at the control which has a slightly finer texture (sandy loam). Water retention capacity for both surface and subsurface horizons is low.

Rock Content

The amount of rock fragments (> 2mm) was estimated for each site and stratified by depth (Mroz *et al.* 1987). The presence of rocks must be considered in determining available soil water, soil nutrients, and bulk density. Whole soil volume must be adjusted by the amount of rock present before calculating these parameters to avoid overestimation of resource levels when expressed on an area basis. Rock fragment estimates showed considerable variation among strata and sites, which is typical in glacial till soils (Table 1.6).

Table 1.6. Summary of rock content (>2 mm) and rock corrected bulk density in the upper 50 cm.

Site	% Rock by Volume	Bulk Density (g/cm^3)
Ground	5-31	1.40
Antenna	2-9	1.46
Control	5-10	1.56

Soil Nutrients

Nutrient content of soils collected during the site evaluation process showed only small variation between test and control sites. These differences were primarily in the A horizons and are the result of varying thickness and composition of the litter layer. For more detailed discussion on the similarity in soil nutrients between sites see Chapter 2, Nutrient Monitoring and Mroz *et al.* (1985).

At the time of site selection, the minor differences observed between these soils were not expected to affect the inherent productivity of the study sites and each site was expected to respond similarly to any environmental influence such as ELF fields (Mroz *et al.* 1984, 1985).

PLOT ESTABLISHMENT EXPERIMENTAL DESIGN

Objectives and Hypotheses

Our broad objective was to assess the impact of ELF fields on forest productivity and health. To accomplish this, more specific objectives were to determine the impacts of ELF electromagnetic fields on:

1) growth rates of established stands, individual hardwood trees, and red pine seedlings,
2) timing of selected phenological events of trees, herbs and mycorrhizal fungi,
3) numbers and kinds of indigenous mycorrhizae on red pine seedlings,
4) nutrient levels of hardwood and red pine foliage.
5) foliage production in the hardwoods.

The ecologically significant subject of insect and disease incidence is discussed in a related project on Litter Decomposition which was conducted at our study sites (Bruhn and Pickens 1994). Ultimately, the question of whether ELF EM fields measurably impact forest communities will be answered by testing various hypotheses (Table 1.7) based on the results of these long-term studies.

Experimental Design

Overview

This study is based on a statistical design to separate possibly subtle ELF field effects on response variables from the existing natural variability caused by soil, stand, and climatic factors. Consequently, to test our hypotheses, it has been imperative to directly measure both plant growth and important regulators of the growth process such as tree, stand, and site factors in addition to ELF fields at the sites. Our approach is to

group similar measurements and analyses by using data from several types of measurements to test a single hypothesis (Table 1.8). The experimental design integrates direct measures with site variables and electromagnetic field exposure and is a common thread through nearly all studies due to the field design.

Table 1.7 Critical hypotheses tested to determine the environmental impacts of ELF EM fields on upland forest ecosystems.

I.	There is no difference in the magnitude or the timing of seasonal diameter growth of hardwoods before and after the ELF antenna becomes activated.
II.	There is no difference in the magnitude of diameter growth of red pine seedlings before and after the ELF antenna becomes activated.
III.	There is no difference in the magnitude or rate of height growth of red pine seedlings before and after the ELF antenna becomes activated.
IV.	There is no difference in the rate of growth and phenological development of the herb, *Trientalis borealis* L., before and after the ELF antenna becomes activated.
V.	There is no difference in the number of different types of mycorrhizal root tips on red pine seedlings before and after the antenna becomes activated.
VI.	There is no difference in the total weight and nutrient concentrations of tree litter before and after the ELF antenna becomes activated.
VII.	There is no difference in the foliar nutrient concentrations of northern red oak trees or red pine seedlings before and after the ELF antenna becomes activated.

Table 1.8. Measurements needed for testing the critical hypotheses of the ELF environmental monitoring program Upland Flora project, and corresponding objectives.

Hypothesis Number	Related Objectives	Measurements
I	1,2	*Weekly dendrometer band readings** Climatic variables, soil nutrients, tree and stand characteristics.
II	1	*Annual diameter growth*, terminal bud size, plant moisture stress microsite climatic variables, number of mycorrhizae.
III	1,2	*Weekly height growth, annual height growth*, terminal bud size, plant moisture stress, number of mycorrhizae, ambient measures.
IV	2	Period measures of plant dimensional variables, including, *leaf size*, and phenological stages of *flowering, fruiting*, etc., climatic variables.
V	3	*Monthly counts of mycorrhizal root tips by type*, climatic variables, tree variables
VI	5	*Periodic collections of litter, nutrient analysis*, climatic variables.
VII	4	*Periodic collections of foliage, nutrient analysis*, climatic variables.

*Underlined print designates response variables; others listed are covariates which are also tested for independence of ELF EM field effects.

Hardwood Plot Establishment

Three permanent 30 x 35 m measurement plots were established in the hardwood stand at the antenna and control sites. The plots at the antenna site were located next to the ELF overhead antenna and positioned 15 m from the right-of-way to minimize edge effect. Three plots of the same size were also established at the control site. However, a 33 x 145 m sham right-of-way was cleared of existing vegetation 15 m from the control plots to provide environmental conditions similar to the hardwood plots at the antenna site. Because the ground site was established only for red pine studies, hardwood plots were not established at that site.

Red Pine Plantation Establishment

Red pine plantations were established at each study site in June 1984. Major reasons for including red pine in the study were: 1) field examination of the sites showed an

inadequate number of conifers necessary for mycorrhizae root studies, and 2) the Michigan DNR expressed concerns about possible ELF effects on forest regeneration and reforestation. Since young trees exhibit more rapid growth rates than older trees, it is possible that ELF effects might be more easily detected on young trees.

A 1.55 ha (average) area at each site was cleared of existing vegetation by whole tree harvesting and immediately planted with 3-0 bare-root red pine seedlings on a 1 x 1m spacing. Seedlings were grown from a Dickinson County, MI seed source at the USFS Toumey Nursery in Watersmeet, MI. A professional tree planter was contracted to expedite the late spring planting, to insure the greatest uniformity in planting, and to maximize the chances for seedling survival. Three permanent measurement plots averaging 46 x 46m were established at each site. Plots at the antenna and ground sites were located as close as possible to the ELF EM source to insure maximum exposure. A 33m strip of the cleared area next to the hardwood plots at the control site was not planted with red pine, to serve as a sham right-of-way. Mechanical vegetation control was necessary in 1986 to remove competing vegetation and again in 1989 to remove woody stump sprouts and aspen root sprouts.

Experimental Design And Electromagnetic Exposure

At the outset of the project, it was known that the EM fields associated with the ELF system would be different at the antenna and ground locations. IITRI has measured 76 Hz electric field intensities at the antenna, ground, and control sites since 1986 when antenna testing began and background 60 Hz field levels were measured at all sites in 1985. Three types of EM fields are measured: magnetic flux density (mG), longitudinal (earth) (mV/m), and transverse (air) (V/m) (Appendix D). Due to the complexity of the effects of site conditions on the air and earth fields, only the effects of exposure levels of the maximum magnetic flux density have been investigated to date. These fields are very predictable and interpretation equations have been developed to estimate maximum flux exposure levels at any location within the study sites (Mroz et al. 1990).

The experimental design is best described as a repeated measures split plot. Each site (control, antenna, and ground) is subjected to a certain level of ELF field exposure and is subdivided into two subunits (hardwood stands and red pine plantations). These stand types comprise the treatments for the second level of the design. Each stand type is replicated three times on a site (where sites represent different levels of ELF field exposure) to control variation in non-treatment factors that may affect forest growth or health such as soil, stand conditions, and background and treatment EM field levels. The time factor in the design is the number of years that an experiment is conducted for baseline to treatment comparisons, or the number of sampling periods in one season for year-to-year comparisons. It is necessary to account for time in the experimental design since for some variables, successive measurements are made on the same plots and/or individual trees over a long period of time without re-randomization. The analyses used differ for different response variables due the measurement frequency and methods. Variations of this general design are discussed in each following chapter as necessary.

Each site follows this design with one exception. There is no hardwood stand at the ground site because buffer strips required to minimize 'edge effects' on plot borders would have resulted in the stands being too distant from the ground for significant exposure to ELF fields.

Analysis of Covariance

Our experimental design directly controls error in the field through replications at the sites. Indirect, or statistical control, can also increase precision and remove potential sources of bias through the use of covariate analysis. This analysis uses covariates which are related to the variable of interest to remove the effects of an environmental source of variation that would otherwise contribute to experimental error. The covariate need not be a direct causal agent of the variate, but merely reflect some characteristic of the environment which also influences the variate.

Covariates under examination vary for different response variables (Table 1.8). Most analyses use ambient climatic variables, such as air temperature, soil temperature, soil moisture, precipitation, and relative humidity, as well as variables computed from these data, such as air temperature degree days, soil temperature degree days, and cumulative precipitation. Depending on the response variable, microsite factors may also be considered. Identification of covariates for different response variables is discussed in detail in the following chapters.

For some response variables, it was possible to develop more realistic models of expected growth and development given the site conditions. In these cases, the analyses of covariance were not used. Instead, the developed models were used to calculate an expected response given the site, stand, and ambient conditions. Deviations from the expected response were examined for evidence of ELF effects on the response variables.

Testing for ELF EM Field Effects

From IITRI data, it is apparent that EM field intensities are affected by vegetative and soil factors. Also, treatment levels have not been uniform over time because of the various testing phases prior to antenna operation. Since the antenna was activated for low-level testing throughout the growing seasons of 1987 and 1988 and full-power operation in May 1989, hypothesis testing examines differences in response variables between these and previous years, and differences between control, antenna, and ground sites in 1987 through 1992 (or 1993 depending on the response variable).

The most extensive comparisons are for yearly and site within year differences. For all hypotheses, ambient and other variables are used to explain site and year differences. Comparisons between pre- and post-operational years are made, as are comparisons

of relationships between sites after antenna activation, to determine whether antenna operation has had a detectable effect on the response variables. For those response variables where analysis of covariance is used, we test to insure that covariates are statistically independent of the EM fields and then examine whether fields explain differences for a particular response variable. If differences are apparent in the modeling efforts, correlation and regression techniques were used to determine whether residuals from these analyses are related to ELF fields.

Detection Limits and Statistical Power

Since each study has been peer reviewed through the years, we feel that the biological basis of each is sound and will contribute to the overall objective aimed at determining whether forest productivity or health has been affected by ELF EM fields. But because of the variability inherent in ecosystem level studies and the subtle perturbations expected from ELF EM field exposure, a quantitative assessment of the level of success and precision achieved by each of the studies in the Upland Flora project is imperative. Two different measures have been considered to make this evaluation, statistical power and detection limits.

Power is defined as the likelihood that a particular statistical test will lead to rejecting the null hypothesis if the null hypothesis is false. Exact calculation of power requires knowledge of the alpha level (Type I Error), parameters of the distribution of the variable of interest under the null hypothesis, and the specification of a given alternative parameter value. In a t-test, for example, to determine power one must know the alpha level (usually 0.05 in the tests described here), the value of the test statistic under the null hypothesis (zero if the test is to determine if two means are different or not), and the degree of difference in the means which is considered biologically important (such as a ten-percent difference). The last value is the most difficult for scientists to agree upon in ecological studies because it is a matter of belief and judgment. Often, quantitative knowledge of ecological relationships is poor and scientists lack the perspective to determine whether a ten-percent difference in a parameter is ecologically significant but a five-percent difference is not. While it is possible to calculate curves showing power for a number of alternative hypotheses, one is still left with the question of how much of a difference is important. An alternative procedure which does not require the specification of this degree of difference is to do an *a posteriori* calculation of the detection limit.

The detection limit is the degree of difference which leads to 50-percent chance of correctly rejecting the null hypothesis (power) for a given alpha level. Use of the detection limit allows an individual reader or reviewer to evaluate the test in light of their own interpretation of what degree of difference is ecologically important. The calculation of detection limits is not exact since it is an *a posteriori* test; it depends on the data used in the test procedure and the procedure itself. In the tables presented in this report, the detection limits were calculated using the results from the analyses of covariance and the Student-Newman-Keuls comparison of means procedure. The

detection limits are, therefore, usually conservative (larger than what may be actually detectable) since additional statistical tests which may be more sensitive to changes in system behavior, such as those utilizing models of expected behavior, are also being performed.

In summary, calculation of statistical power has the advantage of being exact, but the disadvantage for ecological studies of requiring one to specify a specific degree of change that is considered important. The calculation of detection limits has the advantage of not requiring the specification of an alternative (power is fixed at 50 percent), but the disadvantage of being an *a posteriori* calculation; therefore, it is not exact. It is our feeling that the latter quantity, the detection limit, provides information similar to statistical power, but is more suitable for ecological studies since specifications of an exact alternative hypothesis is not required.

SUMMARY

Since the landscape, forest types, and vegetation within the proposed ELF influence area are varied and complex, the careful choice of similar study sites was essential in order to detect potentially subtle ELF EM field effects from the natural variability in selected biological parameters that exist between the test and control sites. Realistically, however, the inherent variability that exists in the overall study area makes exact replication of all factors among the sites impossible to obtain. The sites that were selected for this study were carefully evaluated to insure as much similarity as possible in soil characteristics, microclimate, site history, landform, and the vegetative community. Although differences were observed between the study sites, they were expected to respond similarly to any environmental influence such as ELF fields. A repeated measures split plot statistical design was used to separate possible ELF field effects from the natural variability caused by soil, stand, and climatic factors.

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CHAPTER 2

MEASUREMENT OF CLIMATE AND SOIL VARIABLES FOR DEFINING GROWING CONDITIONS

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ABSTRACT

Climate and soil nutrient contents at the three study sites (control, ground and antenna) were measured to monitor site and year variation in these important environmental factors during the study period. Variation of these factors among sites during the study were also compared to determine if they were independent of antenna operation and to quantify any changes in these environmental variables related to ELF EM induced changes in community structure or productivity. Climate and soil nutrients which were independent of antenna operation were then considered available for use in models and statistical analyses used to evaluate ELF EM effects on other forest ecosystem processes and attributes. ANOVA tests were used to indicate whether changes in climate and soil nutrients among sites during the study were greater than the natural spatial and temporal variation observed at the study sites. Multiple range tests were then used to determine whether these changes were consistent with the operational patterns of the antenna during the study. Finally Pearson's product correlation coefficients were used to determine if these changes were correlated to EM field strengths within the test sites.

Differences in air temperature, soil temperature, soil moisture, and relative humidity for both or one of the site comparisons were found to increase or decrease between the control and both or an individual test site after full power antenna operation. However, these changes were primarily related to inherent site differences in height growth and number of trees which survived the initial planting stress rather than EM field exposure. Only differences in soil temperature at a depth of 10cm between the control and antenna hardwood sites was significantly correlated ($p \leq 0.05$) with 76 Hz magnetic fields. This climatic variable was the only variable not found to be independent of antenna operation. Although we could not conclude that soil temperature at a depth of 10cm was independent of antenna operation, there was no indication that changes in temperature within the hardwood stands were due to any ELF induced alteration of the communities at the antenna site.

Contents of P in the soils at the antenna significantly increased ($p \leq 0.05$) relative to the control in both stand types and differences in soil contents of K between the control and antenna hardwoods significantly increased ($p \leq 0.05$) after antenna operation. The differences in contents between the antenna and control site of K but not P were found to be significantly correlated ($p \leq 0.05$) with 76 hz magnetic flux density measured at the antenna. Given these results we were not able to conclude that soil contents of K within the hardwoods were independent of antenna operation. Since no changes in

contents of K in soils at the ground or antenna plantations were evident it seems unlikely that the changes in soil K within the hardwood was caused by ELF EM field exposure.

INTRODUCTION

Background

Climate and nutrient availability are two of the most important environmental factors contributing to the spatial and temporal variation in organisms, communities, and forest ecosystem processes. Climate and nutrient availability affect a wide variety of plant physiological processes such as photosynthesis, chlorophyll synthesis, cell division, respiration, and nutrient uptake to name a few (Kramer and Kozlowski 1979, Kramer 1983, Jones 1992), whole plant attributes such as apical growth, biomass accumulation, morphology, plant component development, and component quantity (Zahner 1968, Waring and Schlesinger 1985, Landsberg 1986, Spurr and Barnes 1973), and community characteristics such as species distribution, species abundance, and community net primary productivity (Waring and Schlesinger 1985, Kimmons 1987). Since these ambient factors affect such a wide variety of ecological parameters and have such an important role in determining the health and well-being of organisms, one of the major efforts in this study was to monitor these ambient components. This information was then used in physiological and statistical models to account for the variation in health and productivity related to these ambient factors so that we could more fully and accurately evaluate the effects of the ELF EM fields on the various organisms and communities studied.

If climate and nutrient availability are to be used in such a modeling context to make accurate assessments of ELF fields on organisms and communities, it is essential to determine if the variation in specific climate attributes and nutrient availability indices are independent of the EM fields and antenna operation during the study. Conclusions based on models that employ climatic information which is not independent of ELF antenna operation or field strengths would be unreliable or limit our ability to detect ELF field-induced perturbations. Thus the primary effort of this portion of the study was to document whether temporal and spatial variation in climate and soil nutrient availability were consistent with the variation in ELF EM fields at the study site.

Although climate and soil nutrient availability were not considered as response variables in the initial design of the study, it was assumed that any alteration in organism processes or community structures by EM fields could also modify these as well as other ambient variables. Thus this variation was quantified in cases where climate or soil measures were not found to be independent of antenna operation. These data were then compared to measurements of organism and community attributes to determine if changes in the ambient variable corresponded to changes of these attributes as well.

The comparison of organism and community attributes in relation to ambient variables which are not statistically independent of ELF antenna operation can also be used to distinguish between ambient variables which have been indirectly altered by antenna operation from those that randomly covary with antenna operation. Although there may

be no cause and effect relationship between a nonindependent ambient variable and EM fields, it would still be inappropriate to use these variables in physiological or statistical models which are used determine the effects of ELF antenna operation on ecosystem processes.

Objectives and Test Procedures

Air temperature (2 m above the ground), soil temperature and moisture content at two depths (5cm and 10cm), relative humidity, precipitation, air temperature (30cm above the ground), and photosynthetic active radiation (30 cm above the ground) were measured daily at each research site during the growing season from 1985-1993. Macronutrient concentrations were monitored in mineral soil at each study site in June and July each year and analyzed for macronutrient concentration. EM field strength measurements were also monitored at the plots on an annual basis during these study periods (Appendix D). These measurements allowed us to determine:

1) whether selected climate attributes and soil nutrient availability are independent of EM fields and antenna operation;

2) the degree to which nonindependent ambient variables may have been altered by ELF-induced changes in community or organism characteristics.

These objectives were addressed by comparing ambient variable measurements at the control and test sites throughout the study period. An ambient variable was considered to be independent of antenna operation if there was no consistent change in variable magnitude at the test sites with respect to the control site during the full-power antenna operational study period compared to the pre-operation period or if differences in magnitude between the control and test sites were not significantly correlated with the 76 Hz magnetic flux density (magnetic field were used as representative measure of all 76 Hz EM field intensities, Chapter 1) at the test sites during the study.

METHODS

Sampling Methods and Analytical Methods

Climate Monitoring

Air temperature (2 meters above the ground), soil temperature and moisture content at two soil depths (5cm and 10cm) were monitored at each plot in the three study sites. Relative humidity (2 meters above the ground) and precipitation were measured at one plot within the plantations at each site while PAR (photosynthetically active radiation) and air temperature 30cm above the ground were measured in one plot in each hardwoods stand. Global solar radiation was monitored 4 meters above the soil surface in one plot at the ground plantation. Air temperature and relative humidity were measured using Handar 435A relative humidity (thin film capacitor)/air temperature (thermistor) sensors. Soil temperature and soil moisture were monitored using Handar

438A galvanic soil moisture/soil temperature (thermistor) sensors. Precipitation was measured using a Handar Inc. 444A/B rain gauge tipping bucket, and PAR was measured using Licor 190 SB quantum sensor. All sensor signal processing and recording was done by a Handar 540 data acquisition platform at each site. A general sensor configuration for the sites is listed in Appendix B.

Climate monitoring began in late 1984 on a subset of the above mentioned climatic variables. All variables except PAR, air temperature (30cm above the ground), and soil moisture were measured during the growing season beginning in 1985 and each growing season thereafter through 1993. PAR, air temperature (30cm above the ground), and soil moisture were monitored during the growing seasons from 1986-1992. Soil moisture was also monitored during 1993. Air and soil temperatures were also monitored during the dormant seasons on a subset of plots but, frequently, routine maintenance of monitoring equipment during this time made system operation sporadic.

Air temperature, soil temperature, PAR, and relative humidity were monitored every 30 minutes by the Handar, Inc. 540 data acquisition monitoring platform. Global solar radiation was monitored every 60 minutes, soil moisture was sampled every 3 hours, and precipitation monitored continuously. A microprocessor on the ambient system calculates three-hour averages or totals for each appropriate climatic variable. These averages and totals as well as the soil moisture and global solar radiation measurements were transmitted to the GOES East satellite every three hours and relayed to Camp Springs, Virginia. The data were transferred from Camp Springs to a PC computer nightly.

Soil moisture sensors were calibrated each year using bulk soils collected from the sites and dried to four different moisture contents. Soil moisture subsampling procedures were used at each site in order to more accurately measure soil moisture content over the entire area of each plot. Twenty cores were randomly taken from each plot at each site once a month. Moisture content for each depth (5 cm and 10 cm) was determined gravimetrically from a composite of the cores from a plot. These moisture contents were considered to represent the average moisture content for a given plot for the day of core sampling.

Differences between the soil moisture content calculated from the cores and measurements from the soil moisture sensors for a given plot and day of core collection was used as an adjustment for the soil moisture readings for each plot over a monthly time interval. To eliminate any abrupt changes in estimated soil moisture contents between consecutive months because of the monthly adjustment, a weighting equation (2.1) was used to determine the actual monthly soil moisture sensor adjustments. The equation's adjustments for a given month are weighted more heavily to the month of adjustment.

Equation 2.1 Monthly soil moisture adjustment for a specific plot

$$[(CSM_{(M-1)}-SMS_{(M-1)})+2^{*}(CSM_{(M)}-SMS_{(M)})+(CSM_{(M+1)}-SMS_{(M+1)})]/4$$

CSM = Core Soil Moisture from the plot
SMS= Soil Moisture Sensor from the plot
M = Month of Adjustment
M+1 = Following Month
M-1 = Previous Month

Daily averages or totals, maximums, and minimums were computed for each climatic parameter using all 3-hour measurements (eight/day) transmitted by the platforms. If less than six transmissions were received in a day for an air temperature, relative humidity, or solar radiation sensor daily summaries for that sensor are not calculated. Due to the smaller diurnal variability in soil temperature and soil moisture, the transmission limits for calculation of daily summaries for these sensors were four and two transmissions, respectively. Weekly and monthly averages or totals were then computed from these summaries.

Daily averages and totals during the growing season from April 1-October 31 were the basic unit used for comparing site and years in this study element. During some years individual variables were only monitored for a few days in April due to calibration of sensors or the lateness in the month of snow melt and ground thaw. For these variables (soil moisture, relative humidity, and PAR) only May 1 to October 31 measurements were used for analyses.

Weekly averages and totals corresponding to seven day periods in a month were calculated from the daily climatic averages and totals. The first three weeks of a month were averages of seven-day periods and the last week of the month was the average of the remaining days in that month. These weeks were used as repeated replicate samples for each plot during each month of the growing season (refer to statistical analysis section).

Daily climatic averages or totals were occasionally estimated for days in which specific ambient observations were missing as the result of platform and sensor downtime. Methods and criteria used to calculate these values are presented in (Mroz *et al.* 1993). In some instances missing information could not be estimated for a given time period or climatic variable. In these instances these dates were removed from the statistical analyses. Information concerning the removal of these dates is contained in results and discussion section for each climatic variable.

Soil Nutrient Availability

Soil was sampled using a 2.54cm diameter push probe inserted to a depth of 15 cm in the mineral soil. The O_i, O_e, and O_a horizons were removed from the mineral soil prior to probe insertion. Five composite samples made up of 4 randomly selected probe insertion points were collected from each plot at each stand type and site beginning in 1985 in June and July. These samples were dried at 60^oC, sieved and mixed, and

then samples from the two months for a given plot, stand type, site, and year were composited. These composited samples were then analyzed for Kjeldahl N (Bremmer and Mulvaney 1982) and total P (Olsen and Sommers 1982) using a continuous-flow analyzer while exchangeable Ca, Mg, and K (Thomas 1982) were determined using atomic absorption spectrophotometry.

Initially, all nutrient analysis was performed in the year or year following soil sampling. However, since analytical methods changed during this time all samples collected from 1985-1992 were reanalyzed in 1992 and the 1993 samples were analyzed using the above-mentioned methods. Nutrient concentrations were combined with sample depth, soil bulk density and coarse fragment content (Chaper 1) to calculate soil nutrient content for each plot.

Statistical Analysis

Climate Monitoring

Climate at the control and test sites (ground and antenna) was compared to determine 1) possible alterations of microclimate related to changes in forest health or structure and 2) whether climatic variables are independent of antenna operation for use in growth and community development models and evaluations. Alterations in microclimate which could be related to antenna operation were represented in the experimental design as increases or decreases in differences of growing season averages or totals between the control and the test sites after antenna operation for a given climate variable.

A split-plot ANOVA design (Appendix E,Table 1) was used to indicate whether changes in microclimate among sites during the study were greater than the natural spatial and temporal variation for a given climate measure. Changes among sites during the study which could be related to antenna operation were represented by a significant site by year or site-by-stand type-by-year interaction in the analysis. SNK multiple range tests were then used to evaluate if these changes were consistent with the operational patterns (full-power operation in 1989-1993) of the antenna during the study for each climatic variable. Significant and consistent increases or decreases between the control and test sites for a given climatic variable in the years following full-power antenna operation (1989-1993) compared to pre-operation and testing phase (1985-1988) would indicate that the variable may not be independent of ELF antenna operation.

Pearson's product correlation coefficients were then used to make the final determination as to whether these climatic variables were independent of antenna operation. This was done by first computing the differences for a given climate measurement between each test site plot and the control site for each individual study year. Average 76 Hz magnetic flux density was calculated for each test plot (calculated by integrating equations which related annual 76 Hz magnetic flux density measurements to distance from the antenna for a given plot location Mroz *et al.* 1993 Appendix A) for each year of the study. If the differences in a given climate variable

between the test plots and control site were significantly correlated with the magnetic fluxes, it could not be concluded that a specific climate variable was independent of ELF antenna operation. All tests were performed using α=0.05. Detection limits associated with the multiple range tests are presented for each climatic variable (Appendix E,Table 2).

Soil Nutrient Availability

Soil nutrient contents at the control and each test sites (ground and antenna) were compared to determine if these contents were independent of antenna operation. Alterations in nutrient contents which could be related to antenna operation were presented in the experimental design as increases or decreases in nutrient content differences between the control and the test sites after antenna operation. An ANOVA test (Appendix E,Table 3) was used to indicate whether any differences in nutrient content among sites significantly increased or decreased during the nine-year study period. These changes were indicated by a significant site-by-year interaction in the split-plot in space and time design (Appendix E,Table 3). If site-by-year interactions were significant, SNK multiple range tests were used to determine if changes in nutrient contents occurred after antenna full-power operation and whether these changes were consistent with the antenna operation.

If multiple range tests indicated that changes in nutrient content between the control and test sites were consistent with ELF antenna operation, Pearson's product correlation coefficients were then used to make the final determination as to whether a given nutrient was independent of antenna operation. This was done by first computing the differences in content between each test site plot and the control site for each individual study year for the specific element in question. Average 76 Hz magnetic flux density was calculated for each test plot (calculated by integrating equations which related annual 76 Hz magnetic flux density measurements to distance from the antenna for a given plot location Mroz *et al.* 1993 Appendix A) for each year of the study. If the differences in a given soil nutrient content between the test plots and control site were significantly correlated with the magnetic fluxes, it could not be concluded that a specific climate variable was independent of ELF antenna operation. All tests were performed using α=0.05.

RESULTS & DISCUSSION

Climate Monitoring

Temperature

Observed average growing season daily air and soil temperatures for each site and stand type during each year of the study are presented in Table 2.1. Air temperature was consistently warmer at the control than the test sites each year, but there were no consistent differences in soil temperatures between the control and test sites at either depth. Air temperature (p=0.024) and soil temperature 5cm (p=0.012) site-by-year interactions were significant for the control vs. ground comparisons while only soil

Table. 2.1. Average air temperature (AT), soil temperature depth of 5cm (ST5), and soil temperature depth of 10cm (ST10) during the growing season (April-October) from 1985-1993 at each site and stand type.

	YEAR								
	1985	1986	1987	1988	1989	1990	1991	1992	1993
	°C								
AT Plantation									
Ground	11.4	11.9	12.7	12.3	11.8	11.4	12.6	10.4	10.5
Antenna	11.5	12.1	12.9	12.9	12.1	11.7	12.7	10.7	10.6
Control	11.9	12.7	13.6	13.8	13.2	12.3	13.2	11.3	11.0
AT Hardwoods									
Antenna	11.4	12.0	12.7	12.3	11.8	11.4	12.6	10.4	10.5
Control	12.3	12.9	13.5	13.3	12.5	12.3	13.1	11.4	11.1
ST5 Plantation									
Ground	12.5	13.3	13.4	13.2	12.3	12.2	12.5	11.4	11.1
Antenna	12.9	13.5	13.7	13.5	12.6	12.7	12.6	11.0	10.9
Control	12.5	13.5	13.6	13.7	13.2	12.6	12.6	11.0	10.9
ST5 Hardwoods									
Antenna	10.1	11.2	11.6	11.2	10.6	10.7	10.9	9.8	10.1
Control	10.8	11.7	12.3	11.6	11.1	11.1	11.6	10.7	10.5
ST10 Plantations									
Ground	12.2	13.0	13.2	13.3	12.0	11.7	12.3	10.9	10.8
Antenna	12.6	13.4	13.5	13.2	12.5	12.4	12.4	11.1	10.7
Control	12.4	13.3	13.6	13.2	12.7	11.9	12.0	10.7	10.4
ST10 Hardwoods									
Antenna	10.1	10.9	11.7	11.0	10.3	10.4	10.7	9.2	9.3
Control	10.7	11.4	11.5	11.3	10.9	10.9	11.6	10.7	10.5

Figure 2.1

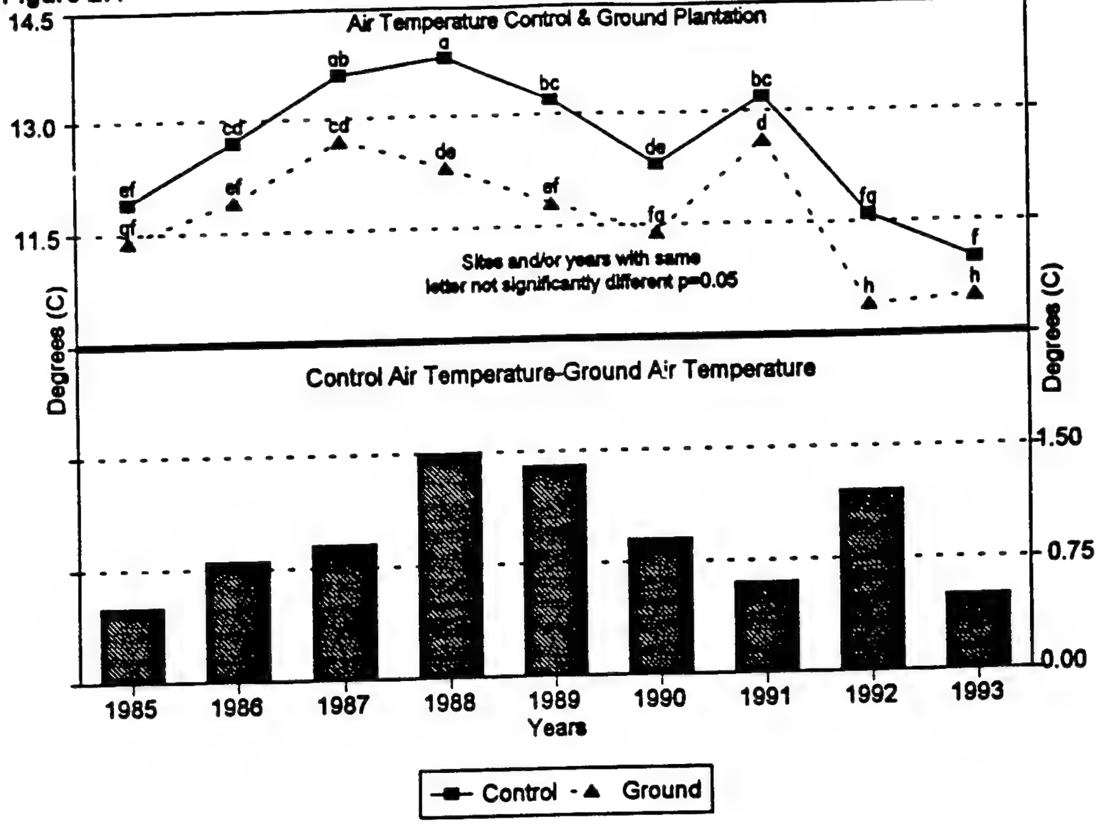
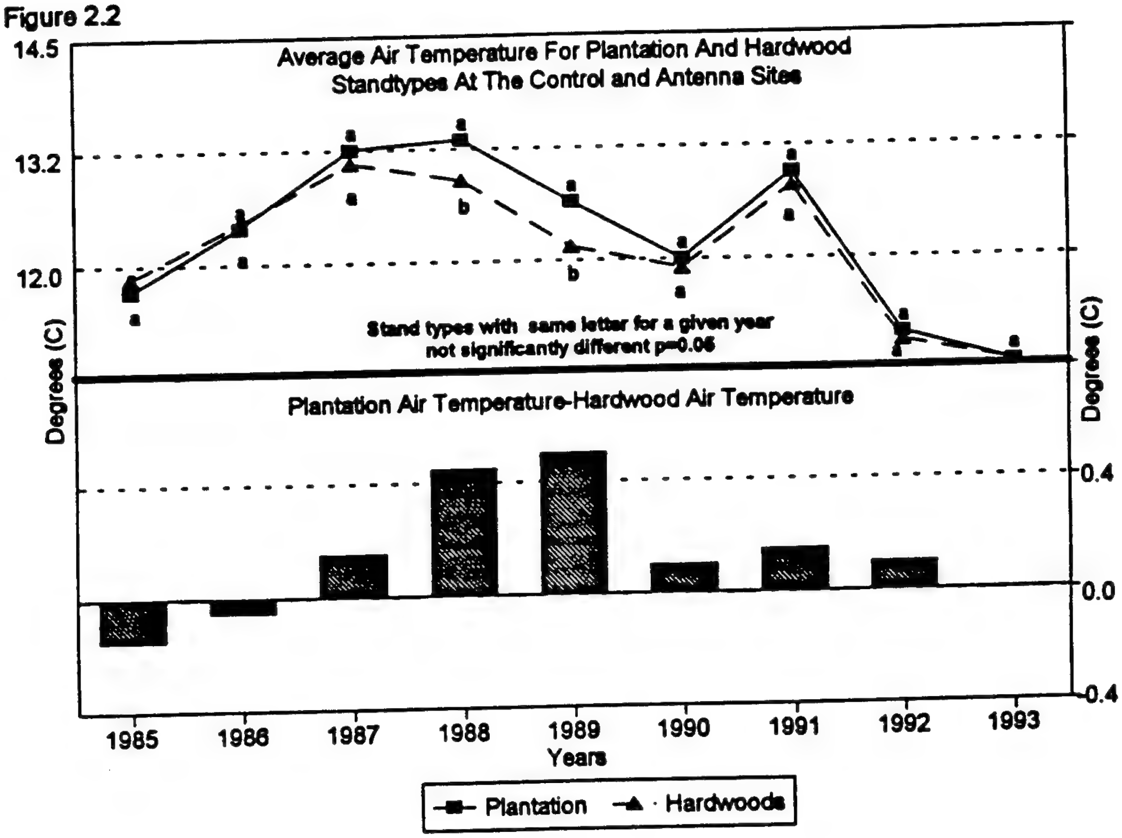


Figure 2.2



temperature 10cm site-by-stand type-by-year interactions (p=0.0.12) were significant for the control vs. antenna comparisons (Table 2.2).

Air Temperature

The significant air temperature site-by-year interactions reflect an increase in differences in air temperature at the control and ground plantations (Figure 2.1) from 1985-1988 (0.5-1.5 ^{o}C) and then a decrease in differences from 1989 to 1993 (1.4-0.5 ^{o}C). Similar changes were also evident when comparing air temperature at the control and antenna plantations,but the magnitude of the changes was less than was observed for the control and ground site (Table 2.1). Differences in air temperature between the control and antenna hardwood stands, unlike the plantations, were stable over the duration of the study (Table. 2.1). Although the decreases in the differences in air temperature between the control and test site plantations occurred after full-power antenna operation, the increased differences from 1985-1988 would suggest these changes may be related to factors which are not related to ELF antenna operation.

Table 2.2 Probability levels associated with ANOVA for air temperature, soil temperature (5cm), and soil temperature (10cm) site-by-year and site-by-stand type-by-year interactions.

	P-Level	
	Site x Year	Site x Stand Type x Year
Control vs Ground		-[1]
Air Temperature	0.024	-
Soil Temperature (5cm)	0.012	-
Soil Temperature (10cm)	0.281	
Control vs. Antenna		
Air Temperature	0.336	0.292
Soil Temperature (5cm)	0.689	0.794
Soil Temperature (10cm)	0.486	0.012

[1] Only the plantation stand type is present at the ground site

Comparisons of air temperature in the two stand types at a given site (Table. 2.1) or the average for each stand type from both the control and antenna sites (Figure 2.2) showed an increase in air temperature in the plantations relative to the hardwood stands from 1985-1989. In 1988 and 1989 air temperatures were significantly ($p \leq 0.05$) warmer in the plantations than in the hardwoods, but prior to or after these years temperatures in the two stand types did not significantly differ. The increase in air temperature in the plantations relative to the hardwoods corresponded to the diminishing distance between the temperature sensor height (2 m) and the height of the

developing red pine canopy (Table 2.3). As the majority of the trees reached or grew above the height of the sensors, differences in air temperature between the two stand types declined (Figure 2.2, Table 2.3). The alteration of air temperature in relation to canopy and sensor height reflects the absorption, storage, and transmittance of short- and long-wave radiation by the canopy surface. At times of low heat loss from evaporation and convection, temperature of air near the surface of the canopy has been found to be as much as 4 °C warmer than ambient air temperatures (Larcher 1983). Temperatures within the canopy are cooler than canopy surface temperatures due to the interception of short-wave radiation by the upper portions of the canopy. The changes in air temperature within the plantations reflect the changes in canopy height in relation to the height of the air temperature sensors.

The modification of air temperature by the red pine canopy not only is responsible for the differences in air temperature between stand types but also the increase and decreases in differences in air temperatures between the control and test site plantations. Growth rates of the trees at the control were greater than the trees at either test site (Table 2.3), and the canopy reached and grew above the height of the sensor much sooner in the control plantation than in the test plantations. Furthermore,

Table 2.3. Mean red pine height (HT), proportion of permanently measured trees between 1.25 and 2.75 m in height (HINT), and number of trees/ ha surviving at the end of each study year (SURV).

	Ground			Antenna			Control		
	HT (cm)	HINT (%)	SURV	HT (cm)	HINT (%)	SURV	HT (cm)	HINT (%)	SURV
1985	22.7	0.0	3416	23.9	0.0	4499	28.3	0.0	5843
1986	38.7	0.0	3191	41.1	0.0	4152	50.9	0.0	5564
1987	63.5	0.0	2959	68.8	0.0	3782	82.7	1.0	5153
1988	95.5	8.7	2745	103.4	16.4	3353	117.7	38.5	4771
1989	141.7	63.7	2505	148.0	79.9	2910	160.8	89.1	4384
1990	181.8	84.5	2277	192.7	91.6	2544	206.3	95.1	4062
1991	228.1	83.4	2072	246.5	73.9	2234	266.5	61.9	3810
1992	284.1	47.3	1880	299.5	28.9	1924	328.7	14.5	3544
1993	338.6	21.6	1757	354.6	11.7	1745	388.1	3.0	3398

a greater number of trees survived theinitial planting stress at the control site compared to the test sites. Thus the differing productivity and stocking of the sites varied the amount and the year in which air temperatures were increased or deceased by the canopy at the three sites. Figure 2.3 demonstrates the effect of the differences in tree heights at the control and ground plantations on the differences in air temperatures at these two sites by comparing the differences in the proportion of trees within 0.75 m of

the 2m air temperature level (DPMT%) to the changes in air temperature differences at the two plantations expressed as an increase or decrease from the average differences during the first two years of the study prior to any canopy sensor interaction (DNATD). Figure 2.3 clearly shows that the changes in temperatures at these sites and the significant site-by-year interactions were related to the greater productivity of the control compared to ground plantations. Since height growth of the red pine appears to be stimulated rather than inhibited by the EM fields (Chapter 3), it does not appear that the air temperature at the test sites has been altered by the antenna operation. Furthermore, comparisons of the differences in air temperature at the control and ground plantation were not found to be significantly correlated with magnetic field strengths (r=-0.225, p=0.268). Given these results, there is no evidence to suggest that the air temperature at the sites is not independent of ELF antenna operation.

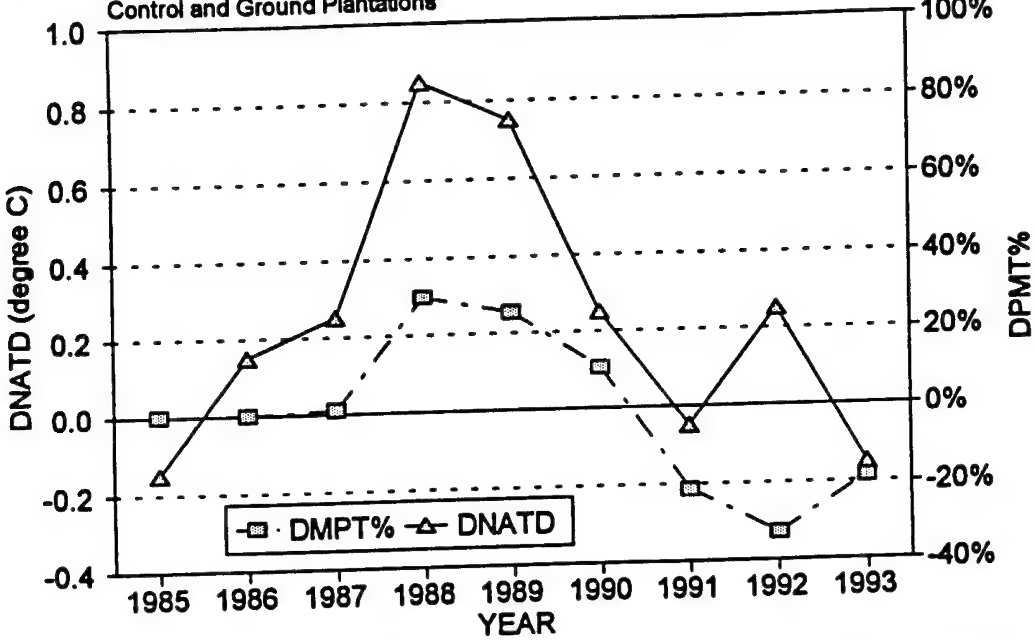
Soil Temperature (5cm)

Comparison of control and ground plantation soil temperatures at a depth of 5cm showed changes similar to those observed for air temperature (Table 2.1). Soil temperature at the control increased with respect to the ground soil temperature from 1985 to 1989, but differences decreased in the years following 1989 (Figure 2.4). For 1992 and 19[illegible] average soil temperature at a depth of 5cm in the control plantation has been lower than temperatures in the ground plantation. Decreases in soil temperatures in the plantations after 1988 (Table 2.1) not only reflect a decrease in air temperature during this time but also a decrease in the amounts of short-wave solar radiation reaching the mineral soil surface due to an increase of foliage surface area and forest floor within the plantations. Changes in the differences in soil temperatures between the control and ground plantations during the study reflect the greater number of trees (Table 2.3) and a faster development of the red pine canopy at the control than at the ground site. Although differences in soil temperatures 5cm between the control and ground plantations changed after full-power antenna operation, the differences were not significantly correlated with magnetic field strengths at the ground site (r=-0.105, p=0.602). The changes in soil temperatures at the plantations were evidently due to the inherent differences in productivity and stocking of red pine at the sites rather than any community perturbation resulting from ELF antenna fields. Therefore, soil temperatures at a depth of 5cm were found to be independent of ELF antenna operation and the resulting EM fields

Soil Temperature (10cm)

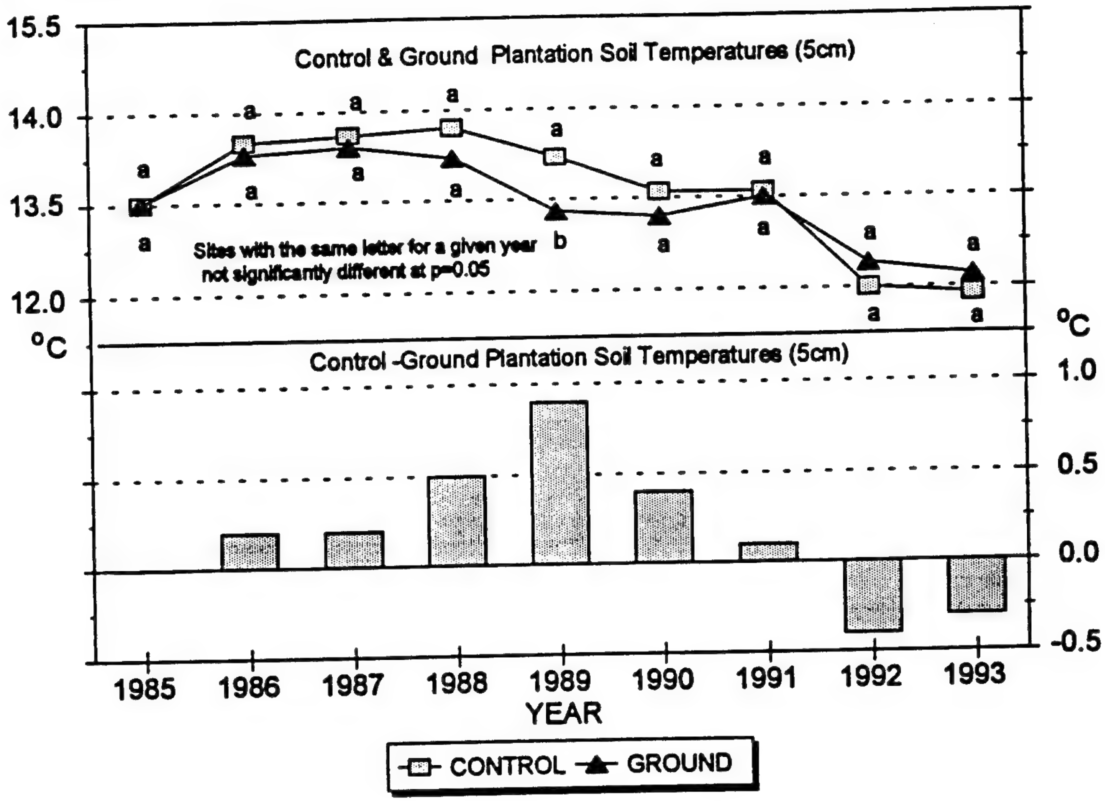
The significant soil temperature 10cm site-by-stand type-by-year interactions reflect an increase in temperatures in the control hardwoods relative to the temperature within the antenna hardwoods after 1990 (Figure 2.5, Table 2.1). Soil temperature at a depth of 5cm within the hardwoods showed a similar trend in 1991 and 1992, but differences between sites in 1993 were similar to differences prior to 1991. Prior to 1991, annual variation in soil temperatures within the hardwoods corresponded to the annual variation in air temperature. Average growing season air temperature was 1.5-2.0^{o}C warmer than average growing season soil temperature 10cm in the control hardwoods and 1.0-1.5^{o}C warmer than average growing season soil temperature 10cm within the

Figure 2.3 Departure From Normal Air Temperature Differences (DNATD) and Differences In Proportion of Trees Within a Height Interval (DMPT) For The Control and Ground Plantations



DNATD= Control -Ground Air Temperature /(Average 1985-86 Control-Ground Air Temperature)
DPMT%=Difference in Proportion of Trees Within the Height Interval (1.25>x>2.75m) at Control and Ground Plantations

Figure 2.4



Control & Ground Plantation Soil Temperatures (5cm)
15.5
14.0
13.5
12.0
°C
Sites with the same letter for a given year not significantly different at p=0.05
Control -Ground Plantation Soil Temperatures (5cm)
°C
1.0
0.5
0.0
-0.5
1985
1986
1987
1988
1989
1990
1991
1992
1993
YEAR
CONTROL
GROUND

antenna hardwoods (Figure 2.6). However differences in air and soil temperature within the control hardwoods was less than 0.7^{o}C in 1992-1993 and in 1991 was 1.8^{o}C within the antenna hardwoods. Changes in the relationships between air and soil temperature at the control appear to be a result of a reduction in leaf area and a resulting increase in insolation within the stand due to the mortality of 31 paper birch trees in 1991 and storm damage to 12 trees in 1992. An indication of the reduction in the amount of foliage and thus leaf area at the control site can be made by comparing the amounts of foliage collected by the litter traps at the two sites. The amount of foliage collected at the control site compared to the antenna site during 1992 and 1993 was less than in any other year during the study (Chapter 4). This reduction appears to have increased the insolation and thus soil temperatures compared to air temperatures within the control site.

The decrease in soil temperature 10cm at the antenna hardwoods compared to the air temperature only occurred in 1991. This change in temperature does not appear to be related to any specific change in productivity measure within the sites. Since differences in air and soil temperature at the antenna hardwoods during 1992-1993 were similar to differences prior to 1991 as well as prior to full-power antenna operation, the change in soil temperature was not found to be related to antenna operation.

Although alterations in soil temperature appear to be unrelated to ELF antenna operation, differences in soil temperature 10cm in the hardwoods at the two sites were significantly correlated ($r=-0.512$, $p=0.006$) with average plot 76 Hz magnetic field flux density within the antenna hardwoods (Figure 2.7). Differences increased with increased field strengths. Given these results as well as the results from the ANOVA test, we cannot conclude that soil temperature at a depth of 10cm within the hardwoods is independent of ELF antenna operation. It does not appear that the change in temperature at the antenna hardwoods in relation to the temperature at the control is a result of a perturbation in any measured community attribute but rather unrelated mortality events at the control site. Soil temperatures at this depth in the plantations were judged to be independent of antenna operations due to the lack of changes in temperatures at the test plantation in relation to the control plantations after antenna operation.

Soil Moisture

Summaries and analyses for soil moisture content were made using observations from May-October due to the lack of reliable measurements in April related to calibration of sensors and the effects of frozen of soil on sensor readings. Average soil moisture contents 5 and 10cm depths during this portion of the growing season from 1986-1993 are given in Table 2.4. Site-by-year interactions were significant for soil moisture 5cm and 10cm control vs. ground comparisons ($p=0.009$, $p=<0.001$) and control vs. antenna comparisons ($p<0.001$, $p=0.003$). Site-by-stand type-by-year interactions were significant for soil moisture content 5cm ($p<0.001$) but not soil moisture content 10cm ($p=0.080$). The significant site-by-year interactions are due to an increase in soil moisture content at the control compared to the test sites in 1990 (example Figures 2.8 & 2.9). This increase occurred in 1990 when moisture contents were at their highest

Figure 2.5

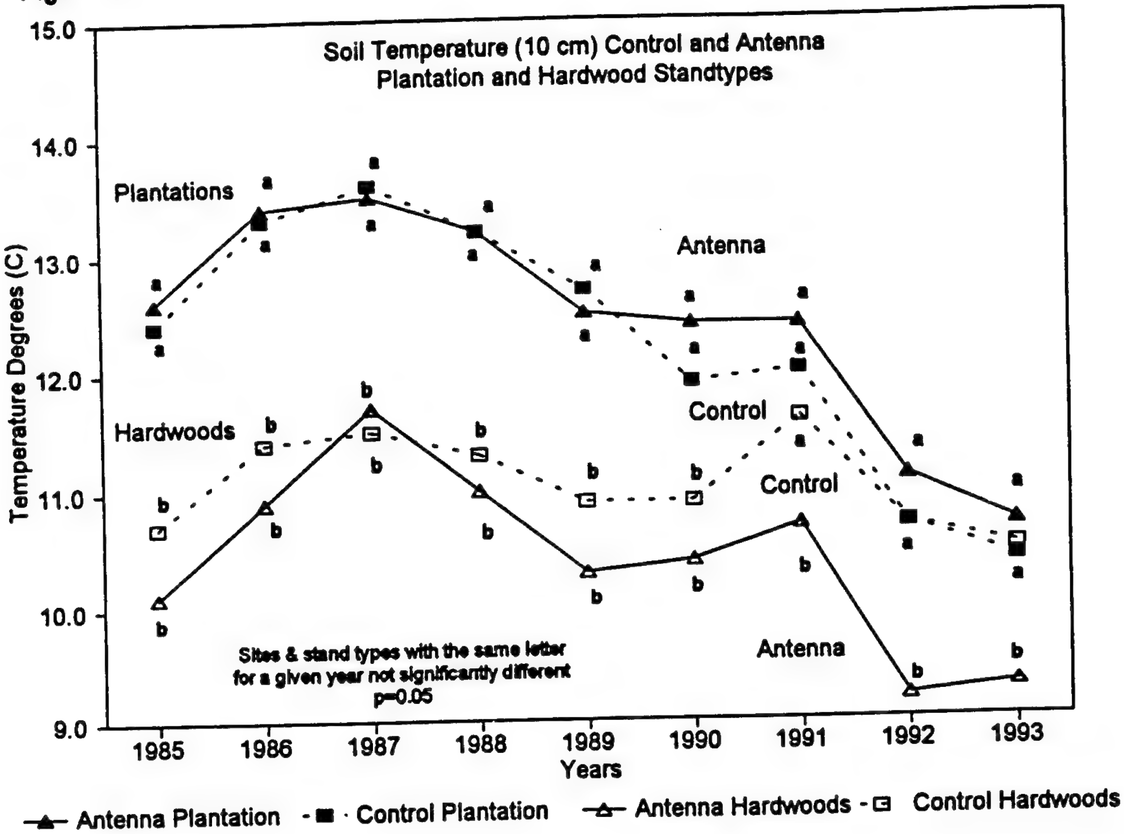


Figure 2.6

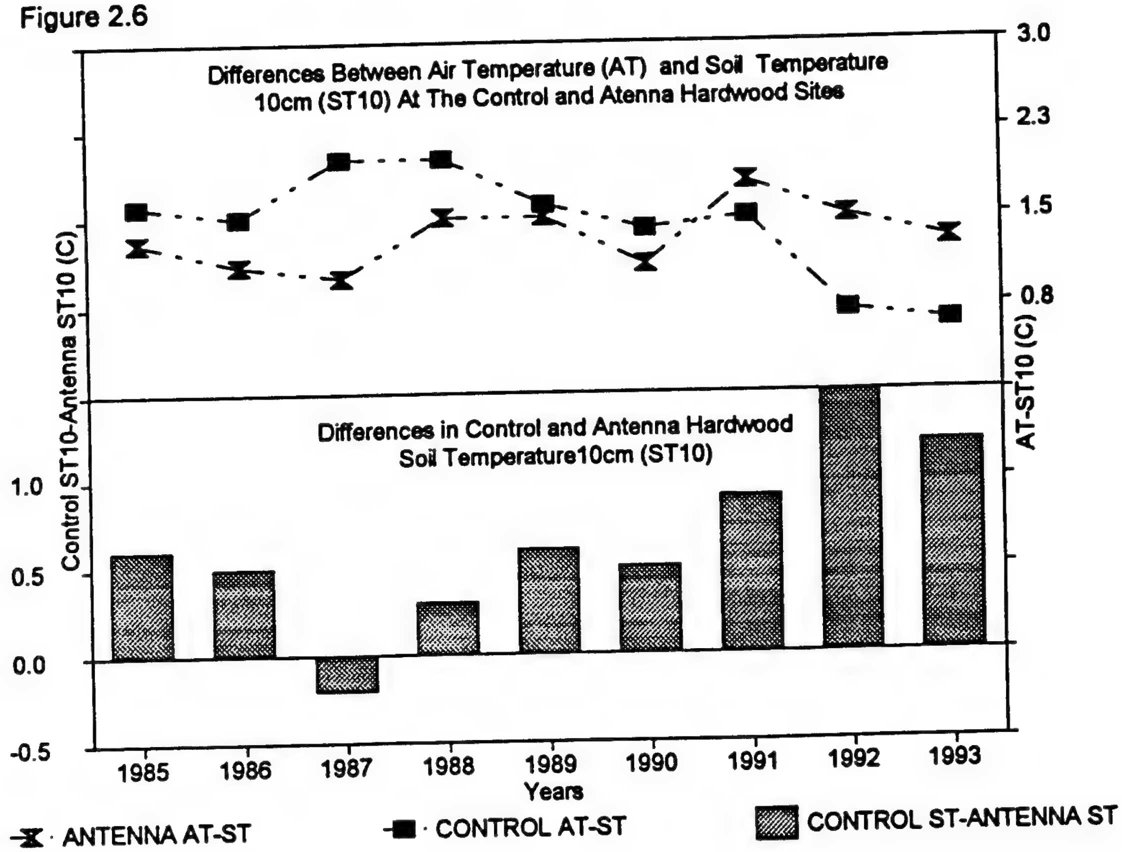
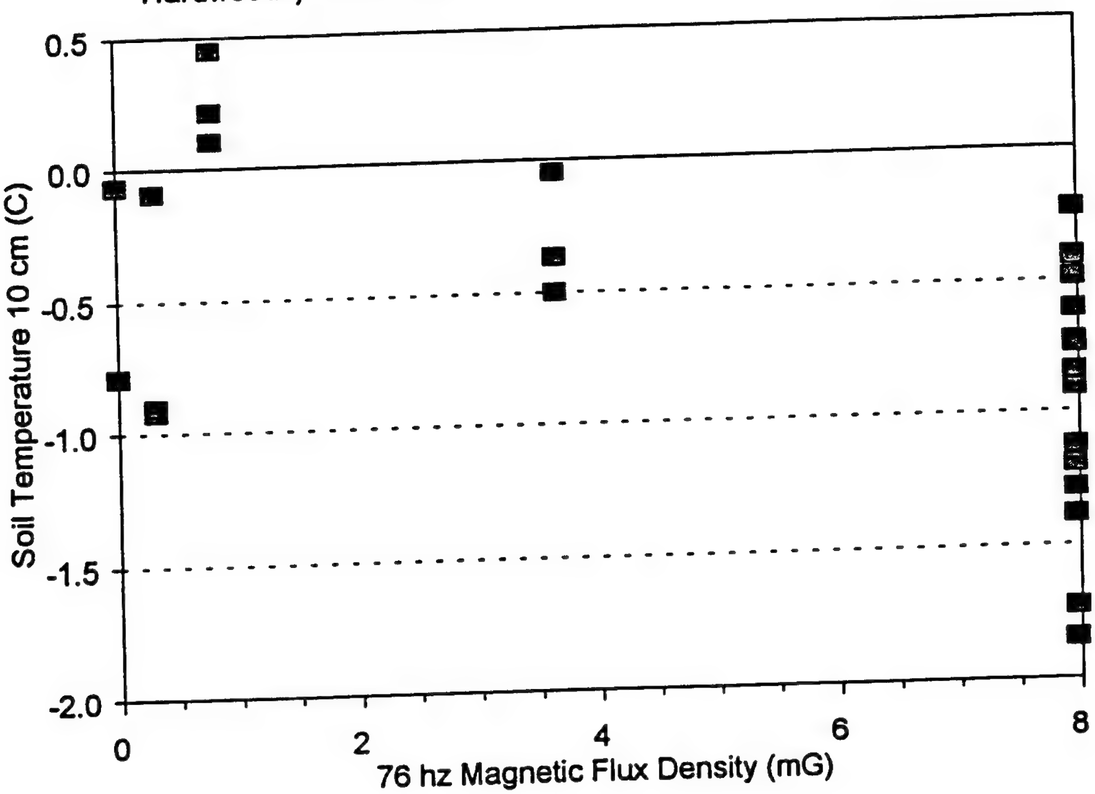


Figure 2.7 Soil Temperature 10 cm vs. Magnetic Flux (Antenna-Control Hardwoods) 1985-1993



levels during the study. This was the only year in which soil moisture contents were significantly greater at the control than the ground plantations. Although soil moisture

Table 2.4 Average daily soil moisture 5 and 10cm during May-October 1986-1993.

	Soil Moisture Content 5cm							
	%							
	1986	1987	1988	1989	1990	1991	1992	1993
Plantation								
Control	15.5	14.1	12.6	14.3	19.7	14.6	15.7	16.2
Antenna	9.0	11.2	11.4	10.2	14.0	13.9	12.1	13.1
Ground	13.1	13.2	12.1	12.2	16.5	15.4	15.4	14.0
Hardwoods								
Control	13.3	10.7	10.1	10.3	16.8	13.9	13.3	15.2
Antenna	10.3	10.9	9.6	9.0	12.8	11.0	13.9	11.4

	Soil Moisture Content 10cm							
	%							
	1986	1987	1988	1989	1990	1991	1992	1993
Plantation								
Control	14.4	15.9	14.4	13.9	18.6	14.5	14.6	14.9
Antenna	9.0	9.8	10.6	10.4	12.4	11.3	11.6	12.5
Ground	15.0	14.2	13.6	14.0	13.7	14.1	14.8	13.9
Hardwoods								
Control	12.0	13.0	12.5	10.9	15.5	12.9	13.3	15.0
Antenna	9.8	11.1	11.0	9.4	12.7	11.6	11.9	11.8

contents were higher at the control than the antenna plantations in all years, differences between the sites were greatest during 1990. The greater differences between the control and test sites during 1990 are related to the greater levels of precipitation received at the control compared to the test sites (Table 2.5) and the greater water-holding capacity of the soils at the control compared to the antenna site (Mroz *et al.* 1993, Element 1).

Comparisons of soil moisture content 5cm within the hardwoods and plantations of the control and antenna sites show similar increases and decreases with changes in moisture regimes for a given year. Differences between sites were generally less during dry years than years with higher moisture contents regardless of which stand type is considered. However, for a given year differences between sites varied within differing stand types. These changes likely reflect the effects of differing levels of evapotranspiration in the two stand types and its effects on soil moisture levels rather

Figure 2.8 Soil Moisture Content (5cm) Ground and Control Plantation

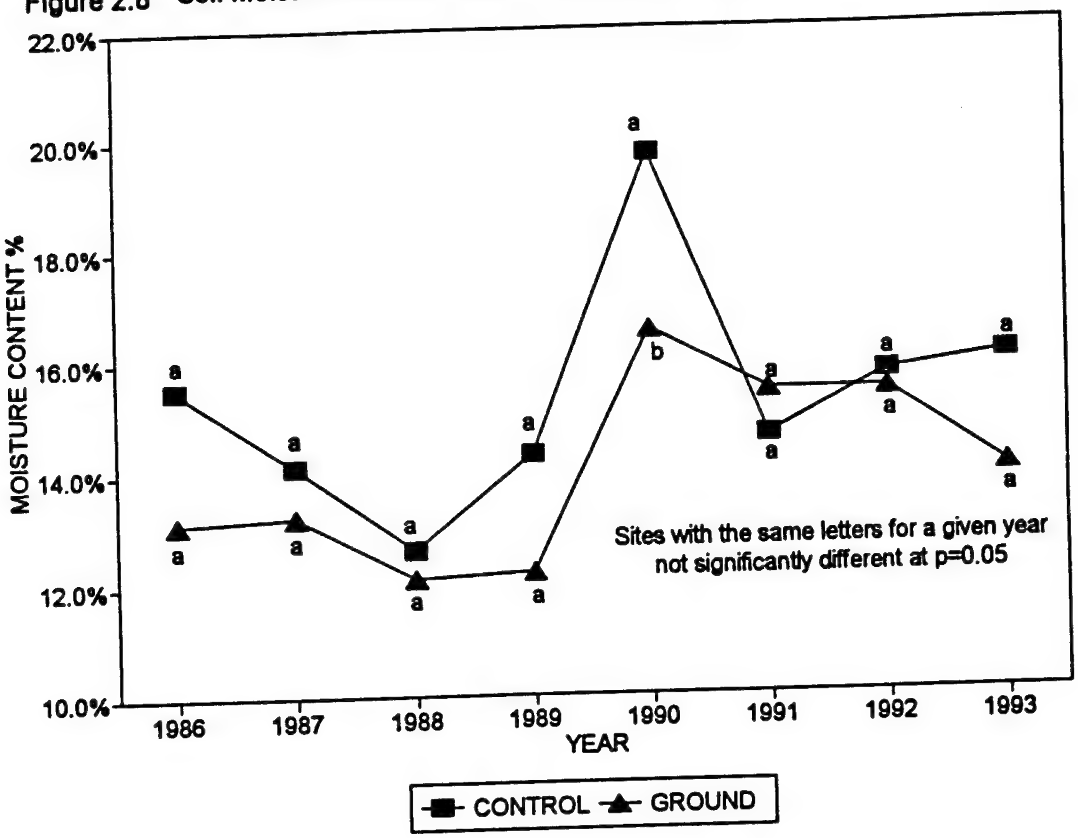
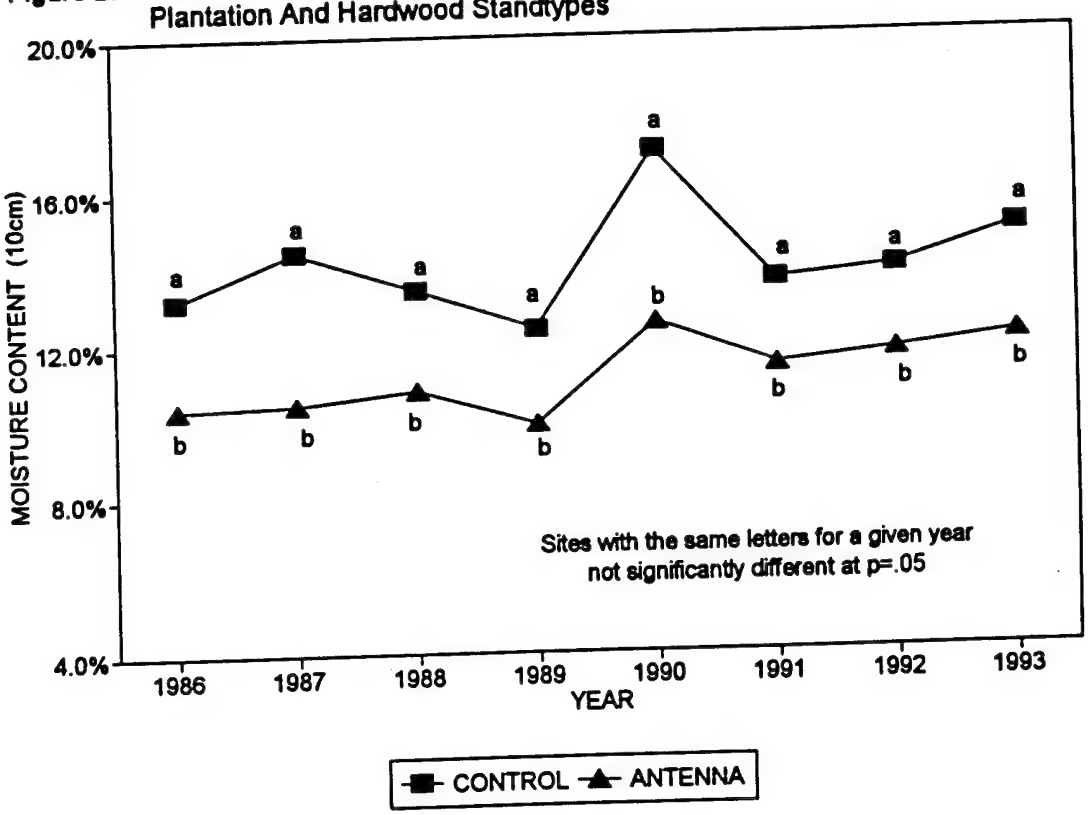


Figure 2.9 Soil Moisture Content (10cm) Control And Antenna Sites,Averages Of Plantation And Hardwood Standtypes



than an ELF effect. Neither annual changes in the relationships of soil moisture content between stand types nor the site-by-year comparisons discussed previously showed any trend which were related to ELF antenna operation. With the exception of soil moisture content 10cm within the hardwoods, differences in moisture contents between the control and test sites were not significantly correlated with magnetic field flux densities. Since site-by-stand type-by-year interactions were not significant for the control vs. antenna soil moisture content 10cm comparisons and soil moisture was not significantly correlated with 76 Hz magnetic flux density within the plantations or at a depth of 5cm, there was no evidence to conclude that soil moisture contents were not independent of ELF antenna operation.

Table 2.5 Average weekly precipitation (April-October), average daily relative humidity (May-October), average daily PAR (May-July), and average daily air temperature 30cm (May-October).

	1985	1986	1987	1988	1989	1990	1991	1992	1993
					Precipitation				
					---cm---				
Control	1.97	1.26	1.78	1.49	0.98	1.80	2.07	1.56	1.73
Antenna	2.46	1.18	1.87	1.77	1.40	1.72	2.09	1.46	1.83
Ground	2.41	1.25	1.78	1.80	1.48	1.60	2.10	1.48	1.81
					Relative Humidity				
					---%---				
Control			70.0	62.5	58.3	70.3	76.9	70.9	75.1
Antenna			84.1	80.0	73.1	87.3	80.3	75.0	78.7
Ground			81.0	78.7	65.9		74.1	72.8	72.3
					PAR				
					---Einsteins/Day---				
Control		4.77	5.06	4.53	3.27	6.42	5.24	4.32	
Antenna		6.33	5.83	6.10	5.56	6.69	5.44	6.71	
					Air Temperature 30cm				
					---^{o}C---				
Control	13.3	13.6		14.8	13.9	13.2	14.1	12.9	
Antenna	12.6	12.8		13.6	12.9	11.9	13.3	11.5	

Precipitation, Relative Humidity, PAR (30cm), and Air Temperature (30cm)

Average weekly precipitation and average daily relative humidity, PAR, and air temperature 30cm for portion of the growing seasons monitored are presented in Table 2.5. Precipitation and air temperature (30cm) site-by-year interactions were not significant ($p<0.05$) for either the control vs. ground or control vs. antenna comparisons; however, relative humidity and PAR site-by-year interactions were significant for the control vs. ground and/or the control vs. antenna comparisons. Multiple range tests indicated that differences in relative humidity between the control and test sites significantly decreased in the years following 1990 (Figures 2.10 & 2.11). Comparison of relative humidity at the sites during each year of the study (Table 2.5) indicated that relative humidity at the control was higher during 1991-1993 than in any

other study year. Changes in relative humidity could be related to the change in height of the canopy in relation to the sensor in much the same manner as air temperatures. Differences in relative humidity between the control and antenna ($r=-0.315, p=0.492$) as well as the control and ground ($r=-0.779, p=0.068$) were not significantly correlated with 76 Hz magnetic flux densities at the test sites. From this information, we concluded the relative humidity at the test sites were independent of antenna operation and that any changes in relative humidity at the sites were related to the effects of the canopy or trees located near the sensor.

Although site-by-year interactions were significant for PAR no consistent change in PAR at the antenna site was evident when comparing preoperational and operational time periods. Differences in PAR at the control and antenna sites were greatest in 1989 and 1992 but were at their lowest levels in 1990 and 1991. Differences in PAR were not significantly correlated to 76 Hz magnetic fields at the antenna ($r=-0.294, p=0.522$). Since no consistent changes in PAR at the two sites were evident and differences in PAR between the two sites during the study were not significantly correlated with 76 Hz magnetic flux density, we concluded that PAR was independent of antenna operation.

Table 2.6 Probability levels associated with site-by-year interactions for precipitation, relative humidity, PAR, and air temperature (30cm)

	Site x Year P-Level
Control vs Ground	
Precipitation	0.969
Relative Humidity	<0.001
Control vs. Antenna	
Precipitation	0.992
Relative Humidity	<0.001
PAR	0.051
Air Temperature (30cm)	0.996

Figure 2.10 Relative Humidity Control and Ground 1987-1989, 1990-1993

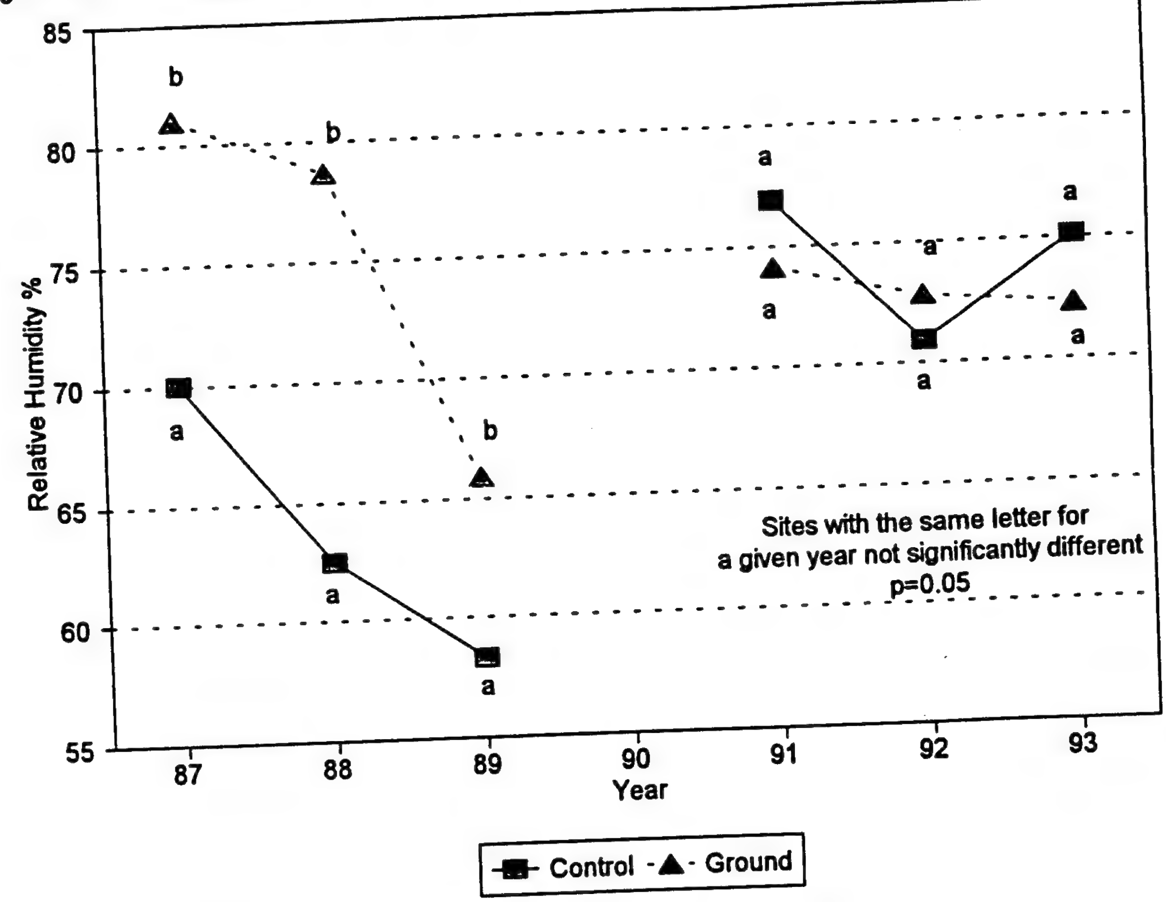
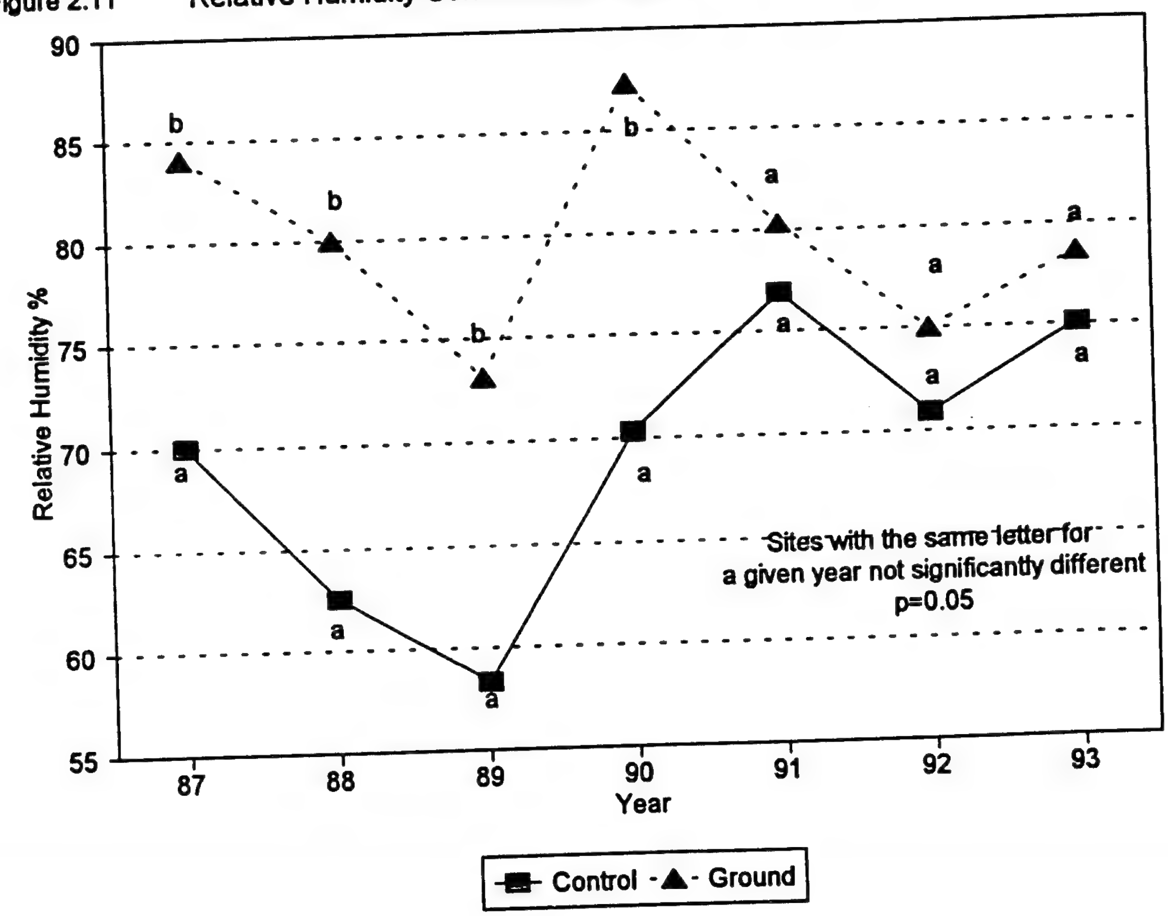


Figure 2.11 Relative Humidity Control and Antenna 1987-1993



Soil Nutrient Availability

Soil N, P, K, Ca, and Mg contents for both the hardwood and plantation stand types are presented in Table 2.7. Contents from 1985 were not included in either Table 2.7 or

Table 2.7. Average June-July soil nutrient content by year for antenna and control hardwood plots.

	1986	1987	1988	1989	1990	1991	1992	1993
					Kg/Ha			
					Hardwoods			
Antenna								
N	1119	1187	929	989	1024	1034	1044	973
P	603	654	586	547	684	600	700	765
K	47	43	42	41	45	26	46	47
Ca	330	216	252	238	172	189	213	228
Mg	37	33	25	43	34	30	36	46
Control								
N	934	1193	1047	1093	961	1038	973	954
P	804	815	774	774	783	813	751	796
K	49	54	49	59	52	45	59	64
Ca	404	384	406	570	319	291	290	305
Mg	41	53	41	67	58	41	53	52
					Plantations			
Ground								
N	1092	1241	1114	1018	1206	1248	1325	994
P	569	529	450	463	603	505	551	584
K	55	57	64	65	73	43	73	69
Ca	455	460	477	430	505	456	560	383
Mg	41	46	39	65	72	46	70	58
Antenna								
N	1033	1056	1003	1017	1026	1057	1095	942
P	671	612	681	555	738	632	732	908
K	55	48	52	54	58	35	65	57
Ca	456	371	351	390	330	305	375	308
Mg	42	33	27	52	49	36	48	46
Control								
N	1104	1235	1175	1120	1230	1153	1232	1107
P	725	829	816	765	855	762	756	853
K	62	68	61	50	67	45	80	76
Ca	554	752	583	760	529	378	668	464
Mg	46	56	42	73	65	40	67	57

the statistical analyses because of the extreme variation in values for both stand types during this year (Mroz *et al.* 1992, 1993). The variation during 1985 within the plantation is believed to be a result of the disturbances related to harvesting and site preparation in 1984 while the initial unfamiliarity with the sampling procedures appear to be responsible for the variation within the hardwoods and to some degree within in the plantations.

Site-by-year interaction probability levels from ANOVA tests as well as detection limits (α=0.05, β=0.50) calculated from the multiple range tests are presented in Table 2.8 for each elemental content and stand type. Phosphorus content site-by-year interactions were significant (p=0.05) for both stand types while Ca and K content site-by-year interactions were significant for the plantation and hardwood stand types respectively. Results from the multiple range tests are presented in Figures 2.12-2.15 for these elements and stand types. Calcium (Figure 2.12) at the control plantation varied

Table 2.8. Significance levels associated with analysis of variance of each soil nutrient content from 1986-1992 in each individual standtype.

	N	P	K	Ca	Mg
Plantations					
			P-Level		
Site x Year	0.895	0.007	0.144	0.001	0.038
			Detection Limit %		
Site x Year	16.1	9.3	20.5	23.4	20.3
Hardwoods					
			P-Level		
Site x Year	0.201	0.015	0.018	0.117	0.249
			Detection Limit %		
Site x Year	15.5	10.7	14.1	41.0	27.7

considerably from 1986-1993. This variation at the control site is responsible for the significant site-by-year interactions for this element. It is unlikely that this variation reflects any actual annual alteration in Ca soil contents but is related to high spatial variation of this element at the control site. Regardless of the cause of the variation there is no indication that Ca contents at the test sites have decreased or increased since antenna operation. However, changes in contents of phosphorus in the soil at both stand types and potassium within the plantations do correspond to antenna operation at the test sites (Figure 2.13-2.15). Levels of P increased while K decreased at the antenna site compared to the control site during the operation time periods.

Fig. 2.12 Soil Nutrients - Plantation Plot, Calcium (kg/ha)

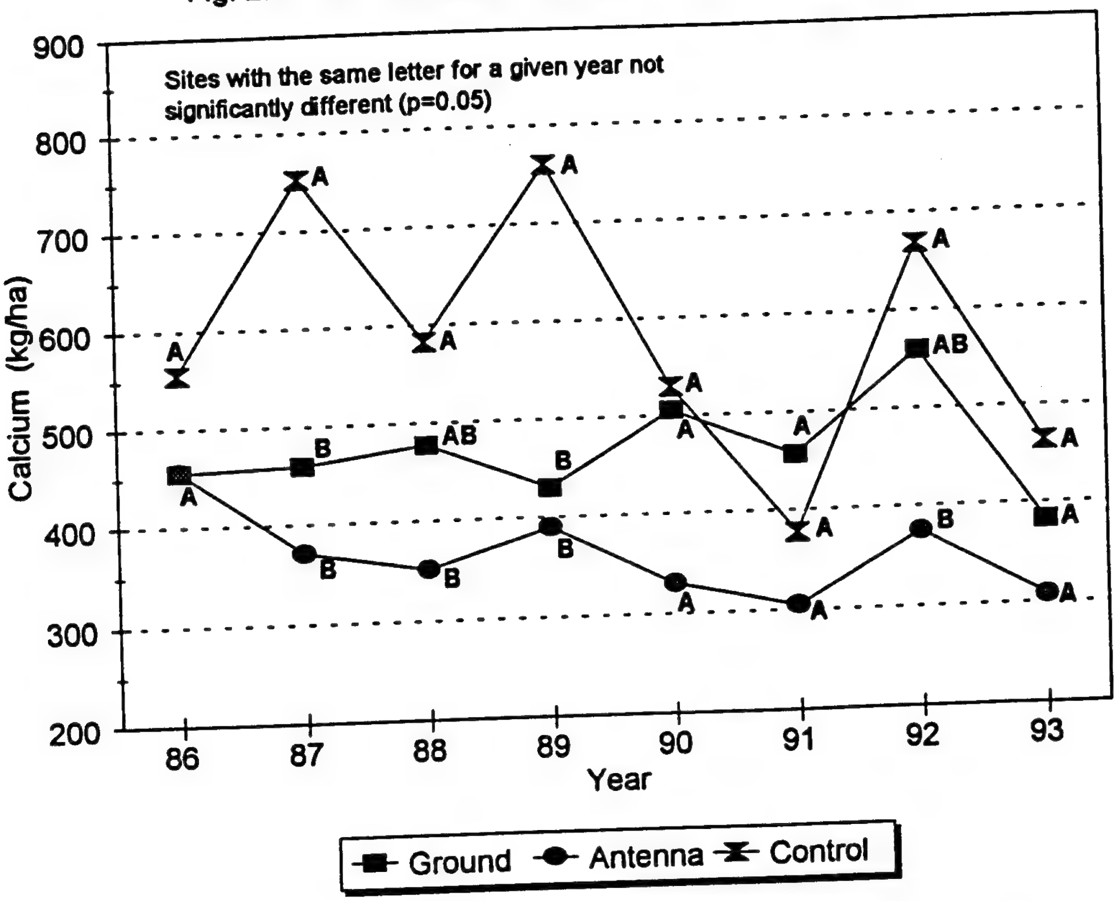


Fig. 2.13 Soil Nutrients - Plantation Plot, Phosphorus (kg/ha)

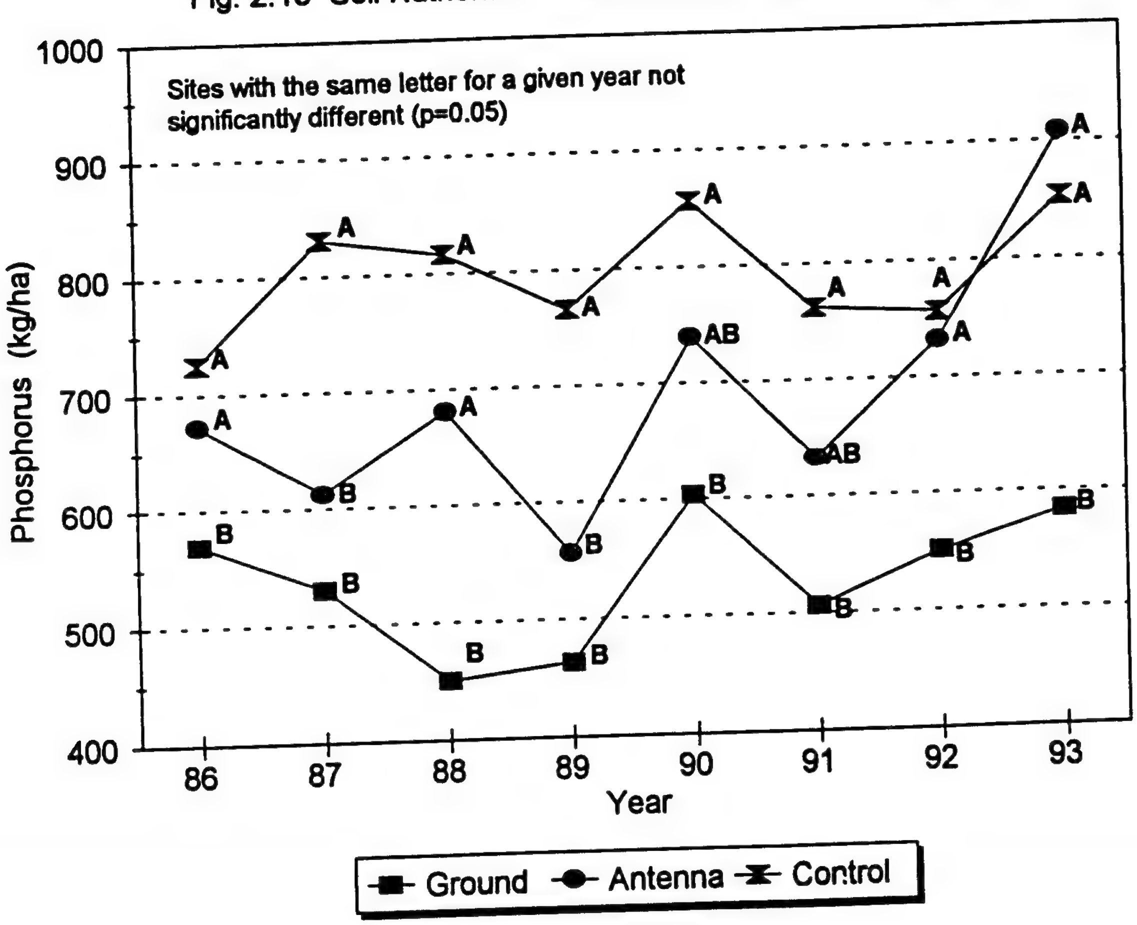


Fig. 2.14 Soil Nutrients - Hardwood Plots, Potassium (kg/ha)

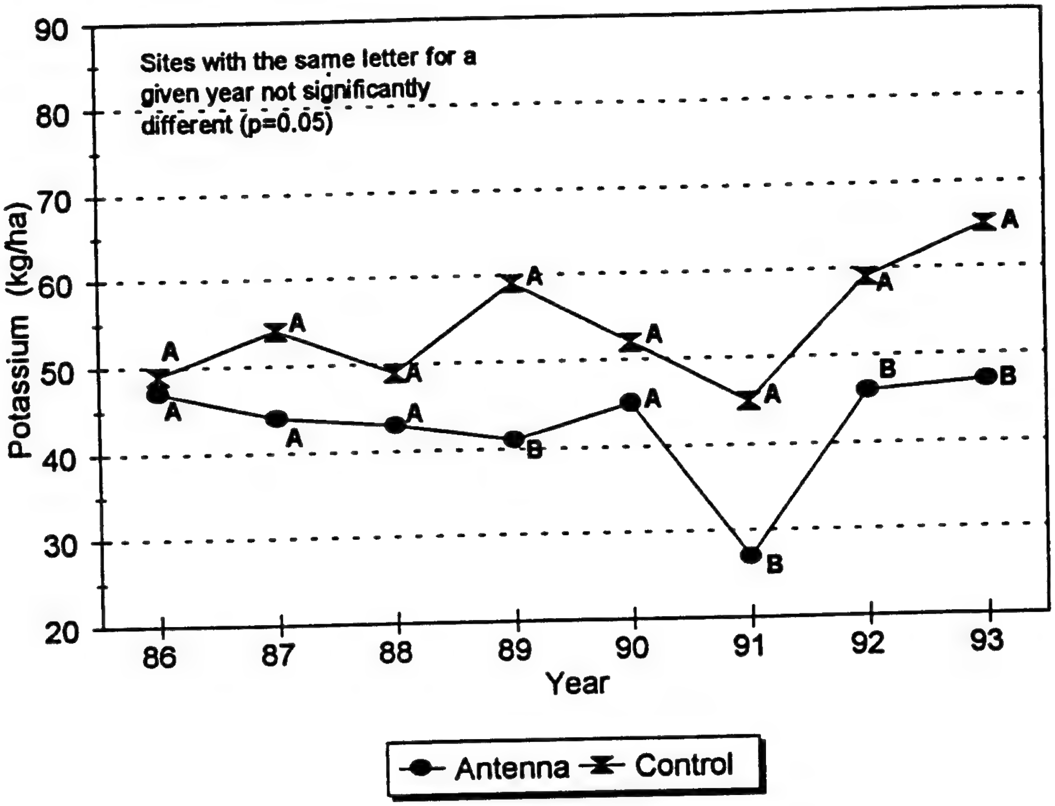
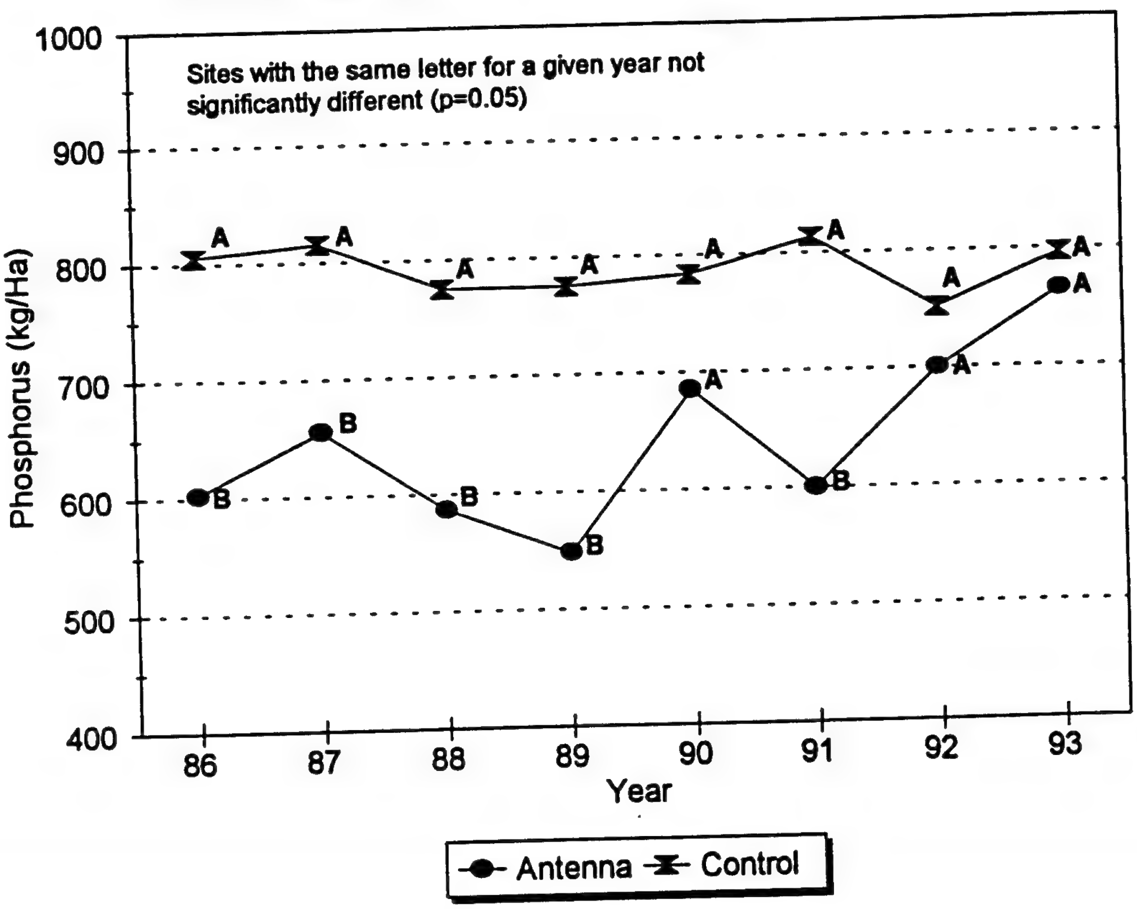


Fig. 2.15 Soil Nutrients - Hardwood Plots, Phosphorus (kg/ha)



Differences in P content between the control and antenna are currently at their lowest levels during the 1986-93 study interval (Figure 2.16).

Differences in P contents between the antenna and control hardwoods ($r=0.294$, $p=0.163$) and plantations ($r=0.120$, $p=0.242$) were not significantly correlated with average 76 Hz magnetic field flux density. However, differences in K content between the antenna and control hardwoods were significantly correlated with magnetic flux density ($r=-0.574$, $p=0.003$). Comparisons of 76 Hz magnetic flux density and differences in K content between the antenna and control hardwoods are shown in Figure 2.17.

Since P contents were not significantly correlated with field strengths, there is no reason to doubt that this nutrient is independent of antenna operation. Due to the significant interactions in the ANOVA and correlations with magnectic field density, we are not able to conclude that K contents in the hardwoods are independent of ELF antenna operation. It is unlikely that the changes in K within the antenna soils is a result of EMF exposure since changes in the soil contents of this element in the plantations were not evident. Irregardless,the changes K at the antenna site occurred at the same time that the antenna system became operational and were significantly correlated with magnetic flux density.

SUMMARY

The majority of the climatic factors and soil nutrients monitored were determined to be independent of the ELF antenna operation and EM fields. Only soil temperature at a depth of 10cm within the hardwoods and soil K contents within the hardwoods were not found to be independent of ELF antenna operation. There was no direct evidence to indicate that any of these factors had been altered at the test sites by ELF antenna operation. However, a consistent change in the relationship between the control and one or more of the test sites with regard to each of these factors was evident after antenna operation which began in 1989.

Fig. 2.16 Differences In P Soil Content Between Antenna and Control Hardwoods and Plantations 1986-1993

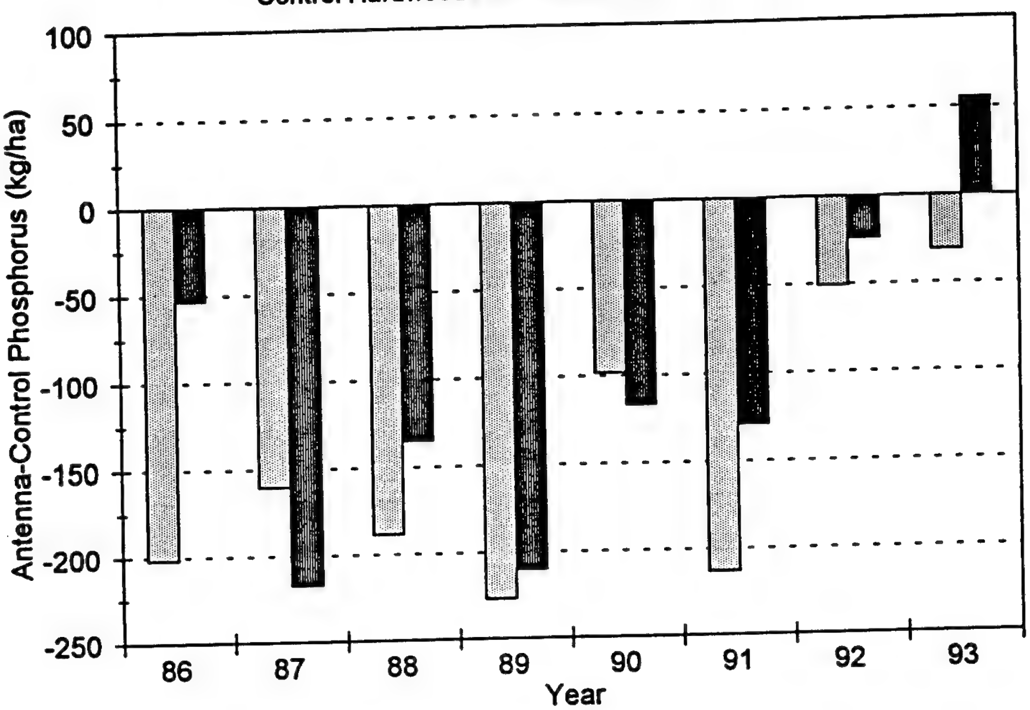
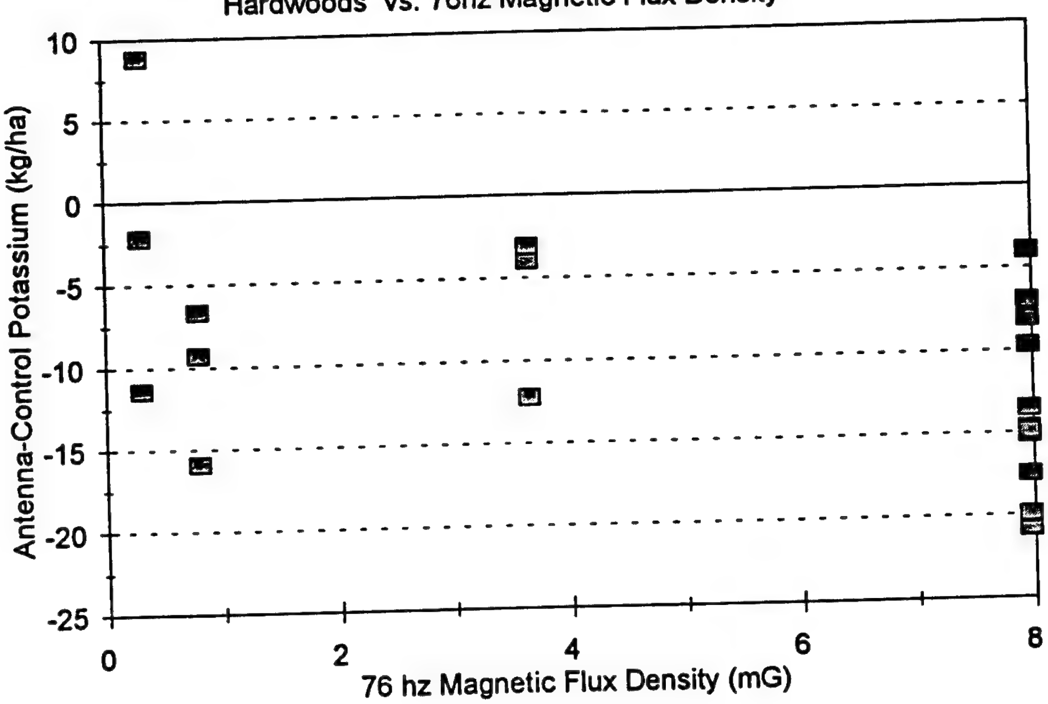


Figure 2.17 Soil K Content Between Antenna and Control Hardwoods vs. 76hz Magnetic Flux Density



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CHAPTER 3

EFFECTS OF 76 Hz ELECTROMAGNETIC FIELDS ON RED PINE AND HARDWOOD GROWTH

David D. Reed, Elizabeth A. Jones, Peter J. Cattelino, Hal O. Liechty, and Glenn D. Mroz

ABSTRACT

The impacts of ELF electromagnetic fields on tree productivity were examined in both the existing hardwood stands and in red pine plantations which were established as part of this study in 1984. Cambial development, as indicated by weekly diameter growth at 1.37m from the ground line, was the primary response variable examined in the hardwood stands. Weekly height growth was the primary response variable in the red pine plantations. In addition, leaf water potential was also examined in the red pine plantations. Seasonal air temperature degree days, July mineral soil potassium concentration, and soil water holding capacity were utilized to account for inherent differences in growing conditions between sites and among years for hardwood diameter growth. Seasonal air temperature degree days and soil water potential were utilized to account for between site and among year differences in red pine height growth.

Mapping tree locations and monitoring ELF EM fields at selected locations across the study sites allowed the determination of EM exposure levels for each tree within the hardwood stands and the red pine plantations. Annual magnetic flux density level was the EM variable used to represent the entire spectrum of EM exposure received by individual trees.

Equations developed during pre-exposure years were used to estimate tree productivity based on annual ambient growing conditions. Differences between the predicted and observed growth rates were examined in relation to the magnetic flux density exposures to determine if EM exposure might be influencing tree growth. Based on analyses through 1992, there are significant ($p<0.05$) relationships between diameter growth and magnetic flux density exposure levels for aspen (*Populus tremuloides* and *P. grandidentata*) and red maple (*Acer rubrum*), and between red pine annual height growth and magnetic flux density level (Figure 3.1).

There is no evidence ($p=0.05$) of an impact of EM fields on the seasonal patterns of hardwood diameter growth or red pine height growth. There is also no evidence ($p=0.05$) of an impact of antenna operation on red pine leaf water potential.

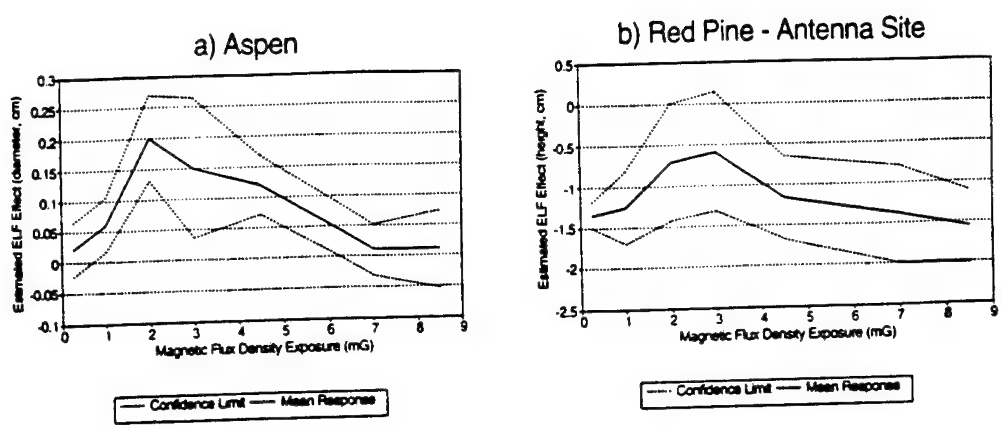

Figure 3.1. Estimated response (and 95% Studentized confidence intervals) to ELF magnetic flux density exposures for a) aspen diameter growth, and b) red pine height growth at the antenna site.

INTRODUCTION

Background

Tree growth is sensitive to a variety of environmental disturbances. The most widely accepted tree growth measurements are diameter at breast height (1.37 m above the ground line) outside bark (dbh) and height. Of these two growth measures, height is the more difficult to measure on mature trees with deciduous species providing particular problems for measurement during the growing season (Avery and Burkhart 1993). The installation of permanent dendrometer bands on the stem of a tree allows measurement of minute changes (0.008 cm) in diameter over short time intervals (Husch *et al.* 1982). Two additional advantages of using dbh as a growth variable are the responsiveness of cambial activity to environmental factors (Smith 1986) and the strong correlation between dbh and total tree biomass (Spurr 1952, Crow 1978). Consequently, measurement of diameter increment is the primary response variable for assessing the effects of ELF fields on deciduous tree growth. Tree height was used for initial stand characterization and study site selection. Deciduous tree growth is being studied at the antenna site and the control site.

At the onset of the study, the Michigan DNR expressed concerns about possible ELF effects on forest regeneration and establishment. Since young trees exhibit more rapid growth rates than older trees, it is possible that ELF effects may be more easily detected on young trees. One year before the right-of-way was cleared for the antenna system, a plantation of red pine (*Pinus resinosa*) was established at both the antenna and ground sites. At the same time, a sham right-of-way plantation study area was cleared at the control site. Basal diameter

and height are used as response variables in the red pine. It is possible to make precise height measurements on the smaller conifers which allowed the use of height in these studies. Basal (groundline) diameter is used in the red pine since trees did not reach breast height until after antenna construction and testing was underway. In addition to diameter and height measurements, foliar moisture stress was also measured on the red pine seedlings.

Hypotheses and Test Procedures

Growth measurements are made on the diameters of the deciduous trees and heights of the red pine seedlings weekly during the growing season. Red pine basal diameter is an annual measurement made at the completion of growth in the fall. Measurement at different times through the growing season allows evaluation of the seasonal pattern or timing of growth as well as the annual amount. Each analysis is designed to evaluate the overall null hypothesis:

> H_0: There is no difference in the magnitude or the pattern of seasonal growth increment before and after the ELF antenna became operational.

This hypothesis is addressed by examining differences in the response variables between the control and the test sites and between post-operational years and previous years. Tests concerning the rate or distribution of growth are made using the growth models described below. Comparisons of post-operational years with previous years are made in part by examining differences between observed and predicted individual tree growth over years and sites.

METHODS

Study Site Description and Sampling Methods

The antenna and control sites are both classified as being the *Acer-Quercus-Vaccinium* habitat type (Coffman *et al.* 1983). The overstory species common to both sites and included in the analyses are northern red oak (*Quercus rubra*), paper birch (*Betula papyrifera*), bigtooth aspen (*Populus grandidentata*), quaking aspen (*P. tremuloides*), and red maple (*Acer rubrum*). Due to the presence of only a few aspen individuals at the sites, the two *Populus* species were combined for the analyses.

The red pine plantations at the antenna, control, and ground sites were established in 1984 following whole-tree harvesting of the existing stands. These areas were planted with 3-0 stock from the US Forest Service Toumey Nursery at approximately a 1 m X 1 m spacing. Mechanical vegetation control was necessary in 1986 to remove competing vegetation; in 1989, it was again necessary to mechanically remove woody stump sprouts and aspen suckers from the plantations.

In the hardwood stands, all trees of the four species over 10 cm dbh were equipped with permanent dendrometer bands in 1984. Tree locations were mapped on a 0.1m grid at each plot. The population of banded trees occasionally added and lost individuals as smaller trees grew above 10 cm diameter and other trees died. Also, bands occasionally needed to be replaced because of damage or growth of the trees. The bands were measured weekly during each subsequent growing season, beginning in mid-April prior to leafout and continuing through mid-October when at least 50% of leaf fall had occurred. This usually resulted in 25-26 weekly measurements of hardwood diameter growth each year.

Following planting, 300 red pine at each site were randomly selected for annual measurements. These seedlings were permanently marked, their locations mapped on a 0.1m grid, and followed through time. Basal diameter was measured annually using calipers on these seedlings. At each site, a subsample of 100 seedlings was selected and measured weekly for height growth. The weekly measurements began in mid-April each year and continued until the middle or end of July when height growth ceased. In addition to the growth measurements, leaf water potential was obtained from destructively sampled seedlings (the same seedlings used in the mycorrhizae studies described in Chapter 5) on a monthly interval in 1985 and biweekly from 1986-92. A pressure chamber was used to determine leaf water potential (Richie and Hinckley 1975).

RESULTS AND DISCUSSION

Hardwoods

The initial (1986) hardwood stand conditions are given in Table 3.1; the annual diameter growth for each of the four species is given in Figure 3.2. Cambial development depends on a complex interaction of tree physiological state, competition from neighboring trees, weather, and physical site conditions. Early in the study, the advantages of using a modeling approach to investigate possible ELF effects on hardwood diameter growth was evaluated. After extensively testing existing models (Fuller 1986), we determined it necessary to develop and test site-specific models to describe the effects of tree phsyiological state, intertree competition, site physical and chemical conditions, and seasonal growth patterns on weekly diameter growth (Reed *et al.* 1992, Appendix B).

Table 3.1 Stand characteristics at the beginning of the 1986 growing season.

Species	Average Diameter (cm)	Average Height (m)	Density (stems ha^{-1})	Site Index (m @ 50 Years)	Age (Years)
Antenna Site					
Northern Red Oak	20.82	22.24	556	22	52
Paper Birch	16.30	20.63	127	18	54
Aspen	22.82	23.51	79	20	55
Red Maple	11.85	16.31	48	18	45
Control Site					
Northern Red Oak	22.69	17.62	143	21	47
Paper Birch	20.42	19.62	25	20	55
Aspen	25.37	20.27	48	21	50
Red Maple	15.23	16.43	410	17	42

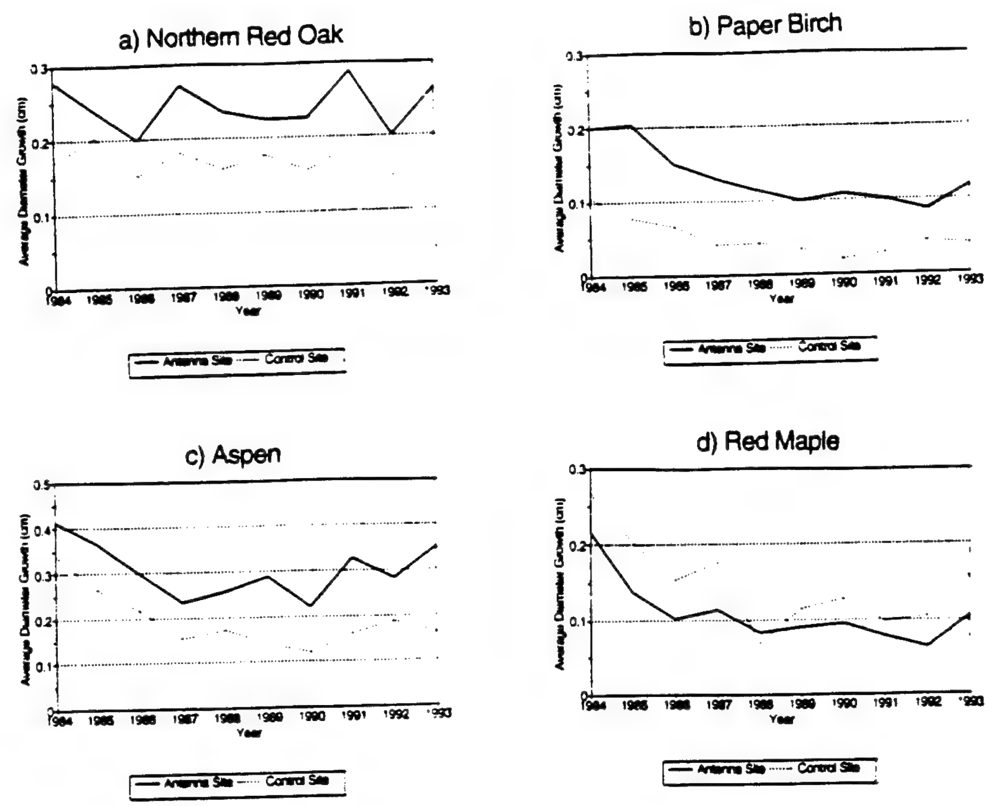

Figure 3.2 Observed annual diameter growth for each hardwood species at each site, 1984-1993.

During growth model development, model coefficients were estimated for each site. There were no significant differences in estimated coefficients between sites, indicating that the trees are responding similarly to the variables in the models at both sites. The sites were combined and a common set of coefficient estimates were used to represent the underlying tree growth trends. The estimated coefficients were species specific.

Cumulative weekly diameter growth is divided into two component parts: total annual growth and the proportion of total growth completed by the date of observation:

$$CG_t = (\text{Total Annual Growth})\ (\text{Proportion of Annual Growth to Time } t)$$

Total annual growth is further divided into the component parts of potential annual growth, the effect of intertree competition, and the effect of site physical, chemical, and climatic properties:

$$\begin{aligned} TAG \quad = \quad & (\text{Potential Growth})\ (\text{Intertree Competition}) \\ & (\text{Site Physical, Chemical, and Climatic Properties}) \end{aligned}$$

Possible ELF effects were tested by examining the yearly differences in total annual diameter growth predicted for each tree and the actual measured values for each tree. Possible changes in seasonal diameter growth pattern were examined by comparing the predicted and observed weekly growth rates. These analyses use observations from all banded trees, including those banded since 1985.

Total Annual Diameter Growth

Differences between the observed and predicted total annual diameter growth were obtained by site and year for each species (Figure 3.3). If there is a change in the way trees are responding to environmental factors then the differences between the observed and predicted growth values will increase. It should be emphasized that the residuals are not the predicted diameter growth values, rather, they are the differences between the predicted and observed diameter growth for each tree.

When examining the diameter growth model residuals for individual trees for several years, it is possible for the results in one year to be correlated with those in the next year. If there were serial correlations in the growth model residuals, this would have to be considered in any analyses of the residuals. The correlation between diameter growth model residuals in successive years was examined for each species on both sites. There were no significant ($p=0.05$)

correlations in the residuals from successive years for any of the species on either site.

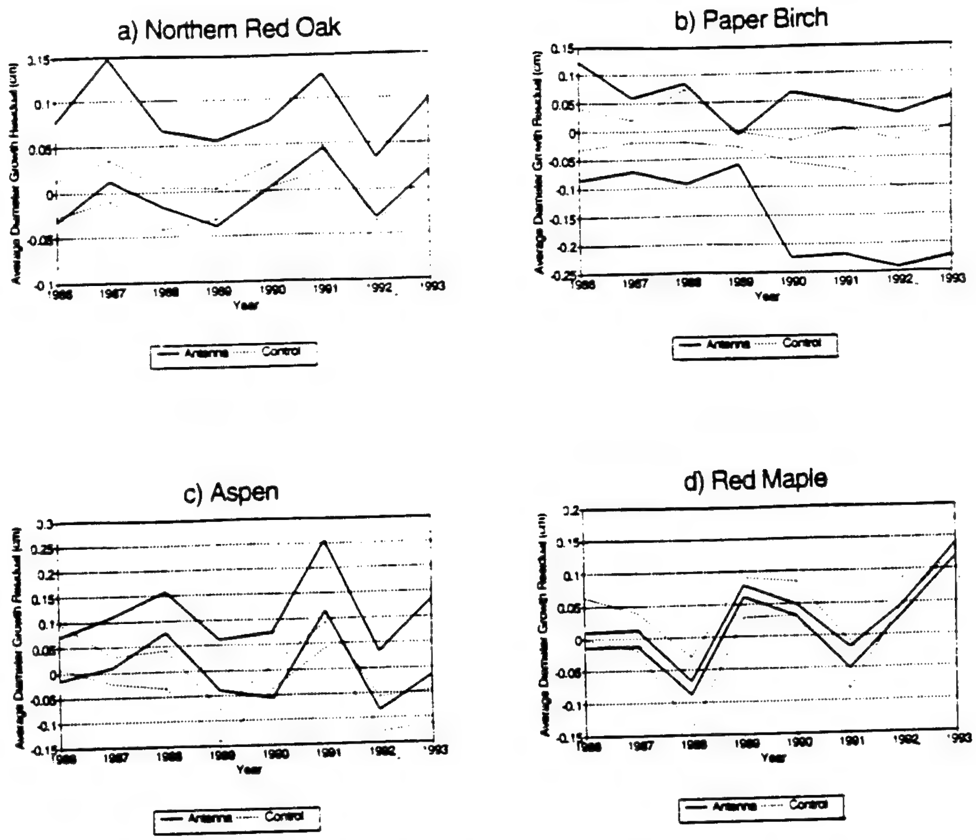

Figure 3.3. Studentized 95% confidence intervals for the average differences between observed and predicted diameter growth for each species on both sites, 1986-1993.

Magnetic flux density exposure levels were estimated for each tree each year by interpolating the field measurements of magnetic flux density levels (Mroz *et al.* 1993). These exposure levels were examined to determine if there were any relationships between the ELF magnetic flux density and the diameter growth model residuals for each species. Reed *et al.* (1993, Appendix B) noted that several other studies (Wiewiorka and Sarosiek 1987, Krizaj and Valencic 1989, Wiewiorka 1990) had reported relationships between plant growth for different species and EM fields. They developed the following model for examining the possible effects of ELF fields on the growth model residuals:

$$R_{Aik} = \alpha_0 + \beta_1 R_{Ck} + \varepsilon_{ik} \qquad mG_{ik}<t_1,\ mG_{ik}>t_2$$

$$= \alpha_0 + \beta_1 R_{Ck} + \gamma_0 + \gamma_1\, mG_{ik} + \gamma_2\, mG_{ik}^{-1} + \varepsilon_{ik} \qquad t_1 \le mG_{ik} \le t_2$$

where R_{Aik} is the residual (observed minus predicted growth) from the ith tree at the antenna site in the kth year, R_{CK} is the average residual from the same species at the control site for the kth year, mG_{ik} is the interpolated magnetic flux density exposure level for the ith tree in the kth year, and t_1 and t_2 are the lower and upper thresholds of effect, respectively. The thresholds were constrained as follows:

$$t_1 = -[\gamma_0 + (\gamma_0^2 - 4\gamma_1\gamma_2)^{1/2}]/2\gamma_1$$

$$t_2 = -[\gamma_0 - (\gamma_0^2 - 4\gamma_1\gamma_2)^{1/2}]/2\gamma_1$$

It is important to note that the growth models were constrained during estimation so that $0 \le t_1 < t_2$. The estimation procedure could, therefore, have estimated the lower threshold at zero or both thresholds beyond the range of data, indicating that there was no ELF field effect on the diameter growth model residuals within the range of data. Furthermore, the model above is constrained to be unimodal between t_1 and t_2, but it could have either been concave or convex, depending on the indications in the data.

For a given species, if no differences in growth exist between the antenna and control sites, then α_0 and β_1 should equal zero. A nonzero value of α_0 indicates an inherent difference in productivity for a given species between the two sites. A nonzero value of β_1 indicates that there is some environmental factor not identified in the growth models which is affecting growth at both sites. In this case, β_1 should be approximately equal to one. If there is no response to ELF fields after accounting for the other factors, then γ_0, γ_1, and γ_2 should all equal zero. Nonzero values of these parameters indicate an effect of the ELF EM fields on tree diameter growth.

For aspen and red maple, γ_0, γ_1, and γ_2 were all different from zero ($p<0.05$), indicating an EM field effect on tree growth (Table 3.2, Figure 3.4, Appendix B). The indicated response was a stimulation of growth with the peak response occurring at 2.4 mG for aspen and 3.2 mG for red maple. The lower threshold was 0.85 mG for aspen and 1.73 mG for red maple and the upper thresholds were 6.79 mG and 6.08 mG for aspen and red maple, respectively. The maximum response was 0.14 cm for aspen and 0.08 cm for red maple. These are increases of 48% and 74%, respectively, over the average diameter growth of the trees since the start of the study. For comparison, these findings are of similar magnitude to responses obtained in nutrient fertilization experiments of aspen (Van Cleve 1973).

Table 3.2. Estimated coefficients and their asymptotic standard errors for ELF exposure equations for each species.

Species	α_0	β_1	γ_0	γ_1	γ_2	t_1 a/	t_2 a/
Northern Red Oak	-0.115* b/	1.058	0.162*	2 E-9*	-0.009	-	-
	(0.195)	(0.051)	(0.180)	(0.002)	(0.001)		
Paper Birch	-0.059	1.131	3.549*	-0.635*	-4.590*	-	-
	(0.008)	(0.063)	(2.343)	(0.471)	(2.901)		
Aspen	0.021	0.178*	0.382	-0.050	-0.290	0.85	6.79
	(0.010)	(0.134)	(0.102)	(0.017)	(0.103)		
Red Maple	-0.032	1.331	0.469	-0.060	-0.635	1.73	6.08
	(0.006)	(0.114)	(0.101)	(0.014)	(0.141)		

a/ The asymptotic standard errors are undefined for t_1 and t_2 due to the constraints in the estimation process. The threshholds were not calculated of γ_0, γ_1, or γ_2 were not asymptotically different from zero (p=0.05).

b/ A * indicates that the estimated coefficient is not asymptotically different from zero (p=0.05).

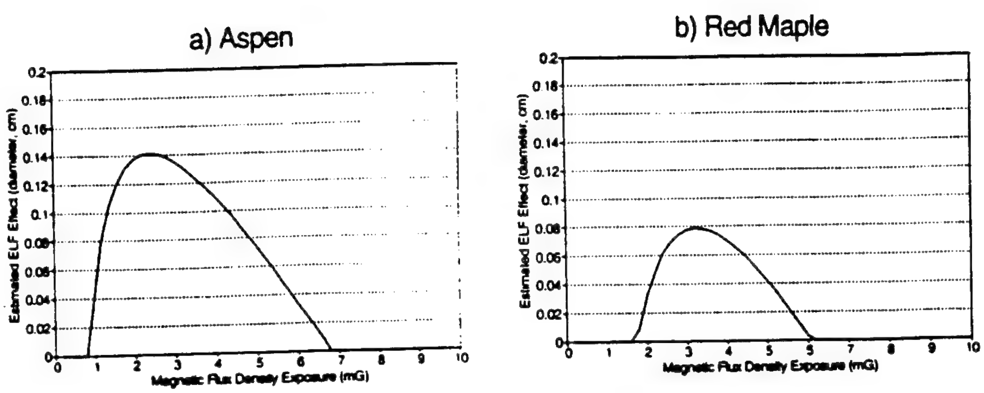

Figure 3.4. Estimated ELF effect on a) aspen, and b) red maple annual diameter increment at the antenna site.

Seasonal Pattern of Diameter Growth

Possible ELF field effects on seasonal diameter growth pattern are examined using the Kolmogorov-Smirnov procedure to compare the distribution of seasonal diameter growth predicted by the growth models (Reed *et al.* 1992, Appendix B) to the observed distribution of seasonal diameter growth on each plot. If an environmental factor is significantly impacting the seasonal diameter growth pattern, the observed growth pattern will differ from that predicted by the model.

The comparisons between the observed and predicted seasonal diameter growth patterns did not indicate any relationships with ELF fields and seasonal growth pattern for any of the four species (Mroz *et al.* 1993). There were very few instances of the observed growth pattern differing from the predicted pattern; out of the 144 comparisons (1986-1992, two sites, three plots per site, and four species), there were four comparisons at the control site (two oak and two aspen) and three at the antenna site (one oak and two red maple) which indicated differences between observed and predicted growth pattern within a year. Based on these results, there is no evidence of an ELF field effect on seasonal diameter growth pattern for any of the four hardwood species in this study.

Red Pine

All seedlings monitored in this study were planted as 3-0 planting stock in the summer of 1984. Figure 3.5 illustrates the survival of seedlings at each site and their average height and diameter at the end of each measurement year. After recovering from planting shock, young trees usually experience exponential growth during their early years. It is this rapid growth and strong dependence on environmental conditions that lead to the use of the planted red pine individuals in this study. These growth rates, as well as seedling survival, are more dependent on temperature and moisture conditions than are the growth rates of mature trees (Benzie 1977, 1982).

Weekly measures of height growth are the primary response variable for investigating possible ELF field effects on the seedlings. Because a weekly measurement period was used, possible ELF field effects on the seasonal pattern of height growth could be examined in addition to analyzing the annual amount of growth. Only annual measurements were made of basal diameter over the life of the study. To further investigate seedling condition, leaf water potential was measured at biweekly intervals through the growing seasons (1987-92).

Red Pine Height Growth

Early in the study, a modeling approach similar to that used to investigate hardwood diameter growth was developed for these analyses. Again, as in the hardwoods, existing models were determined to be inadequate due to poor performance on the study sites. Jones *et al.* (1991, Appendix B) developed a

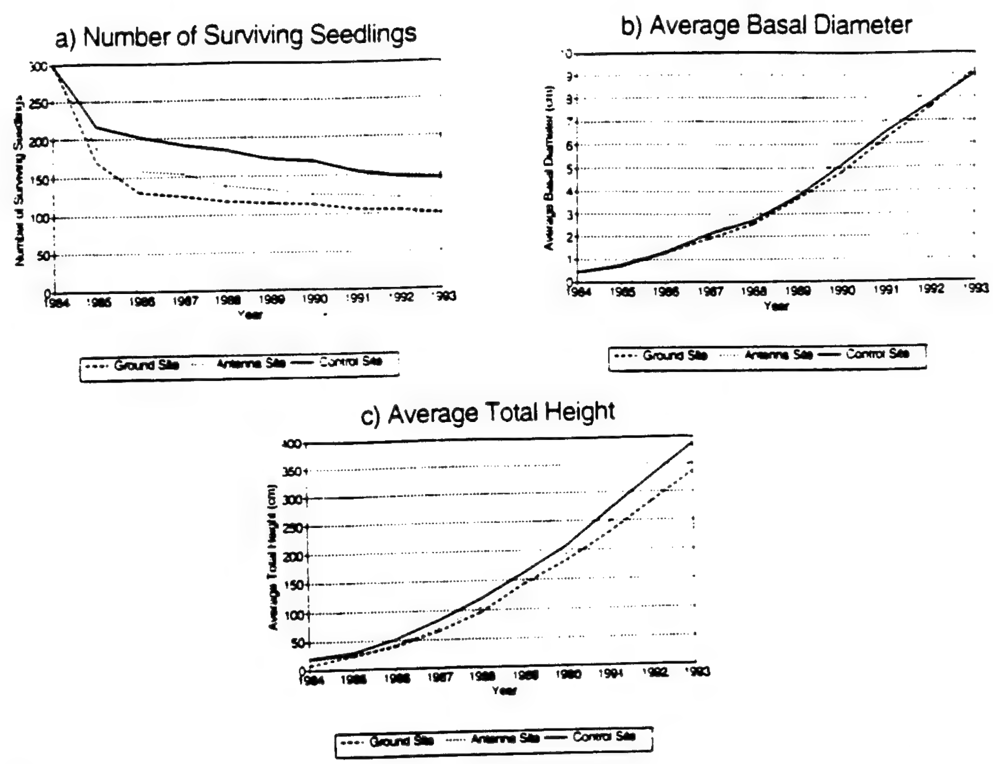

Figure 3.5. Observed a) number of surviving seedlings, b) average basal diameter, and c) average total height for the permanently measured red pine seedlings at the three sites.

height growth model for the seedlings on these sites which relates weekly height growth to air temperature degree day accumulation and soil water potential.

As with the hardwood diameter growth analyses, the red pine analyses utilize differences between the observed annual growth for each seedling and the predicted annual growth for that seedling. Since the plantations were also mapped on a 0.1m grid, estimated magnetic flux density exposure could be interpolated from fixed point measurements for each tree. Relationships between the height growth model residuals and estimated magnetic flux density exposure levels are examined to test if ELF antenna operation is affecting red pine annual height growth. A modeling approach similar to that used in the hardwood diameter growth analyses is used here; residuals from individual trees at the antenna and ground sites are related to magnetic flux density exposure level with the following equations:

$$R_{Tik} = \alpha_0 + \beta_1 R_{Ck} + \varepsilon_{ik} \qquad mG_{ik}<t_1,\ mG_{ik}>t_2$$

$$= \alpha_0 + \beta_1 R_{Ck} + \gamma_0 + \gamma_1\, mG_{ik} + \gamma_2\, mG_{ik}^{-1} + \varepsilon_{ik} \qquad t_1 \le mG_{ik} \le t_2$$

where R_{Tik} is the residual (observed minus predicted growth) from the ith tree at the test (antenna or ground) site in the kth year, R_{Ck} is the average residual at the control site for the kth year, mG_{ik} is the interpolated magnetic flux density exposure level for the ith tree in the kth year, and t_1 and t_2 are the lower and upper thresholds of effect, respectively. The thresholds were constrained as follows:

$$t_1 = -[\gamma_0 + (\gamma_0^2 - 4\,\gamma_1\gamma_2)^{1/2}]/2\,\gamma_1$$

$$t_2 = -[\gamma_0 - (\gamma_0^2 - 4\,\gamma_1\gamma_2)^{1/2}]/2\,\gamma_1$$

As mentioned earlier, the growth models were constrained during estimation so that $0 \le t_1 < t_2$. The estimation procedure could, therefore, have estimated the lower threshold at zero or both thresholds beyond the range of data, indicating that there was no "window" of exposure levels leading to an effect on red pine height growth model residuals within the range of data. Furthermore, the model above is constrained to be unimodal between t_1 and t_2 but it could have either been concave or convex, depending on the indications in the data.

As with the hardwood analyses, if no differences in growth exist between the test and control sites, then α_0 and β_1 should equal zero. A nonzero value of α_0 indicates and inherent difference in productivity for a given species between the two sites. A nonzero value of β_1 indicates that there is some environmental factor not identified in the growth models which is affecting both sites. In this case, β_1 should be approximately equal to one. If there is no response to ELF fields after accounting for the other factors, then γ_0, γ_1, and γ_2 should all equal zero. Nonzero values of these parameters indicate an effect of the ELF EM fields on red pine height growth.

For red pine height growth at both the antenna and ground sites, γ_0, γ_1, and γ_2 were all different from zero ($p<0.05$), indicating an EM field effect on tree growth (Table 3.3, Figure 3.6, Appendix B). The indicated response was a stimulation of growth with the peak response occurring at 2.2 mG at the antenna site and 4.0 mG at the ground site. The lower threshold was 0.68 mG at the antenna site and 2.73 mG at the ground site while the upper thresholds were 6.80 mG at the antenna site and 5.72 mG at the ground site. The maximum annual response was an 0.83 cm increase in height growth at the antenna site and an 0.63 cm increase in height growth at the ground site.

Table 3.3. Estimated coefficients and their asymptotic standard errors for ELF exposure equations for red pine height growth at the antenna and ground sites.

Site	α_0	β_1	γ_0	γ_1	γ_2	t_1[a]	t_2[a]
Antenna Site	-0.144* [b] (0.145)	1.107 (0.085)	1.959 (0.337)	-0.262 (0.070)	- 1.208 (0.450)	0.68	6.80
Ground Site	-0.247 (0.079)	0.882 (0.049)	9.669 (4.113)	-1.144 (0.503)	-17.865 (8.057)	2.73	5.72

a/ The asymptotic standard errors are undefined for t_1 and t_2 due to the constraints in the estimation process. The threshholds were not calculated of γ_0, γ_1, or γ_2 were not asymptotically different from zero (p=0.05).

b/ A * indicates that the estimated coefficient is not asymptotically different from zero (p=0.05).

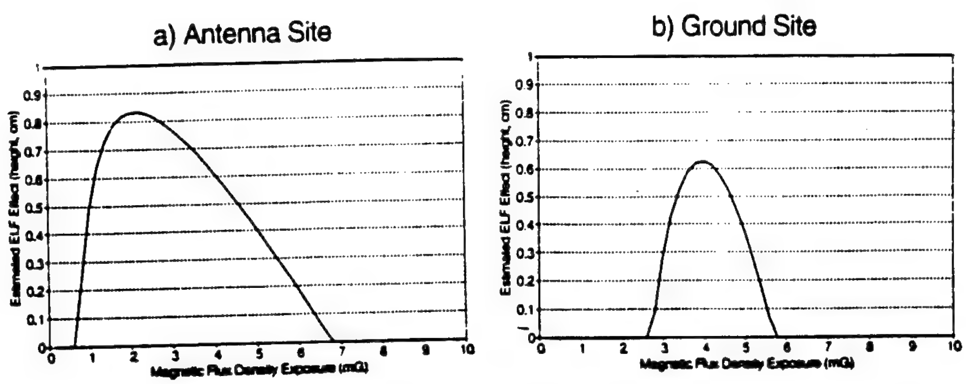

Figure 3.6. Estimated ELF effect on red pine height growth at the a) antenna site, and b) ground site.

Seasonal Pattern of Height Growth

Possible ELF field effects on seasonal red pine height growth pattern are examined using the Kolmogorov-Smirnov procedure to compare the distribution of seasonal diameter growth predicted by the growth models (Jones *et al.* 1991, Appendix B) to the observed distribution of seasonal diameter growth on each plot. The height growth model predicts seasonal pattern of shoot elongation from

air temperature degree day accumulation and soil water potential. If an environmental factor is significantly impacting the seasonal diameter growth pattern, the observed growth pattern will differ from that predicted by the model.

The comparisons between the observed and predicted seasonal red pine height growth patterns did not indicate any relationships with ELF fields and seasonal growth pattern (Mroz *et al.* 1993) for any site or year. There were no instances of the observed growth pattern differing from the predicted pattern ($p=0.05$). Based on these results, there is no evidence of an ELF field effect on seasonal red pine height growth pattern at either the ground or antenna site.

Red Pine Diameter Growth

Red pine annual diameter growth was analyzed using a repeated measures split plot analysis of covariance with plots nested within sites. The covariates used were cumulative air temperature degree days through August, July mineral soil total Kjeldahl N concentration, and available water at 10 cm depth during the month of August. All covariate values were from the current year of growth. A modeling approach was not taken; measurements within the growing season were not made until 1989 so there were no measurements prior to antenna operation to develop baseline relationships.

There were significant differences ($p<0.05$) in red pine annual diameter growth among sites and years. There were differences among sites both prior to antenna operation as well as after full-power operation in 1989. The relative differences among sites were consistent before and after antenna operation. The differences in annual diameter growth among years are also consistent with the exponential growth pattern for young seedlings in the period following adaptation to the site following planting and before the onset of competition. Examination of the site-by-year interactions using a multiple range test indicate that most instances of changes in the relative rankings among sites occurred prior to antenna operation; there is no evidence of a significant ELF EM field effect on red pine annual diameter growth.

In a related analysis, Zhang *et al.* (1994) examined the factors affecting red pine biomass increment on the three sites during the 1989 growing season. They found that differences among the sites could be explained by site physical and climatic factors. This provides further evidence indicating that there is no detectable influence of ELF fields on red pine annual diameter growth.

Red Pine Leaf Water Potential

The analyses of leaf water potential measurements discussed here were conducted using data collected biweekly during the growing season from 1986 through 1992. Measurements made during 1985 were not included in the analyses for two reasons: 1) there were cold temperatures during the initial and final measures for that year, and 2) there was a different sampling interval (monthly) compared to subsequent years.

Literature suggests that leaf water potential is strongly related to soil moisture and temperature (Nambiar *et al.* 1979, Hinckley *et al.* 1978, Fahey and Young 1984, and Teskey *et al.* 1984). Abrams (1988) noted a great deal of variability in leaf water potential of non-droughted plants. In this study, leaf water potential rarely exceeded -.5 MPa and then only for short periods in the middle of the summer. As a consequence, leaf water potential was significantly ($p<0.05$), but weakly correlated with precipitation between measurement dates ($r=0.12$), average daily temperature ($r=0.14$), and average daily minimum relative humidity ($r=0.11$). Using these factors in an analysis of covariance, leaf water potential was found to differ among years, but not among sites; there was a significant site X year interaction but, examining these differences with a multiple range test indicated that the differences were not consistent over time and appeared unrelated to the ELF field exposure levels (Mroz *et al.* 1993).

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CHAPTER 4

EFFECTS OF 76 HZ ELECTROMAGNETIC FIELDS ON HARDWOOD LITTER PRODUCTION AND FOLIAR NUTRIENT CONTENT OF RED OAK AND RED PINE TREES

Martin F. Jurgensen, Peter J. Cattelino, and Hal O. Liechty

ABSTRACT

Litter fall is important for the transfer of nutrients and energy within a vegetative community. This makes litter production a good indicator of possible ELF field effects on forest ecosystems. Litter samples were gathered at frequent intervals during the growing season at both the antenna and control hardwood sites. This provided an estimate of change in canopy production prior to and during ELF antenna operation. Litter was collected from five $1m^2$ traps located in each of three permanent measurement plots established in uncut hardwood stands. Samples were separated into leaves, wood, and miscellaneous components, and a subsample of leaf litter was further separated by tree species. All litter samples were weighed and analyzed for N, P, K, Ca, and Mg contents.

Leaf samples were also taken during the growing season from: 1) various sized northern red oak trees (15 cm, 21 cm and 32 cm diameter) growing on both the antenna and control sites , and 2) red pine seedlings planted on all three sites. The samples were used to monitor possible ELF effects on leaf weight (red oak) and nutrient accumulation (red oak and red pine).

Annual total litter fall amounts varied considerably between the antenna site and the control site. Covariate analysis using stand and environmental variables that affect foliage production rates was used to reduce litter fall variability between the two sites, and increase the possibility of detecting ELF effects. Soil and air temperatures generally showed the highest correlations with litter production, and gave the best results when used in the analyses of covariance. These statistical tests using eight years of litterfall showed no detectable effects of the ELF antenna field on litter weight.

Average nutrient concentrations of the various litter components and for individual tree species showed considerable variability between the antenna and the control sites. Covariate analysis was again used to try and separate possible ELF effects from site and ambient factors. These results showed that significant litter nutrient concentration differences existed between sites prior to antenna construction and were not affected by the ELF antenna operation.

Nutrient concentrations in red oak foliage during the growing season varied between the antenna site and the control, but these generally reflected the nutrient status of the sites before antenna transmissions began. Similar results were found for leaf weight. Red pine foliar concentrations were not significantly correlated with 76hz magnetic flux

densities. Consequently, differences in red oak and red pine foliage nutrient concentrations and weight among the three study sites were not related to operation of the ELF antenna.

INTRODUCTION

Background

Litterfall and decomposition play an important role in nutrient cycling, soil development, and carbon dynamics in deciduous forests (Vogt et al. 1986). Litterfall weight and nutrient concentration data are often used to represent foliage production rates, site quality, and nutrient efficiency in forests. These factors are responsive to tree physiological changes and external influences which control the rate, timing, and amount of litter production (Fyles et al. 1987). Leaf samples taken during the growing season for nutrient analysis and weight determination would also monitor nutrient accumulation and subsequent nutrient translocation from the foliage prior to leaf fall (Mead 1984). These physiological processes are often affected by various natural or anthropogenic sources before external signs of stress are evident (Margolis and Brand 1990), and would be a potential indicator of ELF field effects.

Objectives

The objective of this study was to obtain information on total litter weight and nutrient content, and foliar nutrient levels of northern red oak and red pine during the growing season prior to and during the operation of the ELF communication system. Two overall null hypotheses were tested in this study:

H_0: There is no difference in the total weight of litter fall (leaves, wood, and miscellaneous) before and after the ELF antenna became operational.

H_0: There is no difference in the foliar nutrient concentrations of northern red oak and red pine trees before and after the ELF antenna became operational.

These hypotheses were addressed by examining the differences in litter total weight and nutrient content, and foliar nutrient concentrations of northern red oak and red pine growing on the ELF study sites prior to antenna operation (1985-1988) and after antenna tranmission began (1989-1993).

METHODS

Antenna Operation

Measurements of 76 Hz transverse (electric field in air), longitudinal (electric field in earth), and magnetic fields were made on both study site each year (Chapter 1). Due to the complexity of the effects of site conditions on the air and earth electric fields, only the maximum magnetic flux exposure levels have been spatially quantified across the study sites. The magnetic field variation was very consistent across the sites and interpolated equations have been developed to estimate maximum magnetic flux densities at any point within the study sites. These equations, together with litter trap and red pine seedling locations mapped to the nearest 0.10 m (Reed *et al.* 1989), provided estimates of magnetic flux exposure at the center of each litter trap and for individual seedlings.

Sampling and Data Collection

Litter

Five 1m2 litter traps were used to monitor tree litter production on each of three 30x35 m permanent measurement plots at the antenna and control sites. Litter was collected monthly during the summer and weekly during the onset of leaf fall in mid-September. All litter was separated into leaves, wood, and miscellaneous categories and weighed. Additionally, leaf litter from a 0.25 m2 compartment in each trap was separated by tree species. Samples were composited from each collection date to provide a foliage sample for nutrient analysis representative of the growing season.

Foliage

Crown nutrient concentrations and translocation in northern red oak leaves were examined by collecting foliage samples monthly at both sites during the summer months. An analysis of stem diameter data indicated that sampling trees of 15 cm, 21 cm, and 32 cm would adequately represent the distribution of red oak on each site. Three trees of each diameter were located adjacent to the permanent measurement plots at each site to minimize disturbance. Leaf samples were obtained from near the top of the crown using a 12-gauge shotgun with a full choke. All litter and foliage samples were dried at 60^{O}C in a forced draft oven, and were ground to pass a 40-mesh sieve for subsequent N, P, K, Ca, and Mg analysis. A representative subsample of ten leaves was also taken from each foliage collection and weighed.

Foliar nutrient concentrations in planted red pine seedlings were monitored by removong all one-year-old fasicles from 15 seedlings per site in October of each year. Approximately 100-200 fasicles were randomly selected for nutrient analysis, dried at 60^{O} C, ground, and analyzed for concentrations of N, P, K, Ca, and Mg.

Nutrient Analysis

Concentrations of total N and P in litter and foliage were determined using a semi-micro Kjeldahl method and a continuous flow analyzer. Ca, Mg, and K were measured by atomic absorption spectrophotometry after ashing and dissolution by hydrochloric acid. The National Bureau of Standards (NBS) red pine foliage standard was used as a quality control measure for Ca, K, and Mg.

Design and Analysis

The productivity and health of forest ecosystems is directly related to the environmental factors which influence the individual ecosystems. In order to quantify the variability in litter production and foliar nutrient concentration, the effects of environmental factors such as microclimate and other ambient conditions had to be determined before the effect of a single and potentially subtle factor, such as EM fields emitted by the ELF antenna system,could be quantified. Analysis of covariance (ANCOVA) was used to determine if climatic and site characteristics could be used to explain the natural variation in litter production and nutrient concentration (see Appendix G). Prior to ANCOVA, regression analysis were used to select climate and soil nutrient variables that explained significant variation in litterfall weights and foliar nutrient concentration. These variables were then considered for inclusion in the SNK Multiple Range Test. An ELF effect was indicated by: 1) a significant site-by-year interaction in the ANCOVA, and 2) multiple range tests that show significant differences between the control and test sites after the antenna is in operation. An alpha level of 0.05 and a beta level of 0.50 was used for all analyses. Detection limits were also determined from the SNK tests. When a significant site x year interaction was found for litter production and nutrient content, 76 hz magnetic flux density values were used as a covariate to see if ELF field effects removed site differences. More detailed information on specific statistical analyses of litter and tree foliage data are given in Mroz et al. (1993).

Potential effects of ELF fields on red pine nutrition were further investigated by comparing site differences between foliar nutrient concentration for a given nutrient to the 76hz magnetic flux density estimated for a given seedling location in a test site. Only trees sampled in 1990-1993 were used for this part of the study because prior to 1990 tree locations were not recorded, and/or the antenna was operated at varying levels of power during the year of foliage development. Consequently, red pine ELF exposure represents the variation in field strengths within plots, not variations in tree exposure prior to and after the operation of the ELF antenna. Relationships between magnetic fields and differences in foliar nutrient concentrations between the control and sample trees at the test sites were quantified using Pearson's product moment correlation coefficients.

RESULTS AND DISCUSSION

Litterfall Weights

Over the eight years of this study, leaves comprised between 75 - 80% of total litterfall on both sites. While the amount of woody litter showed a stronger site x year effect than foliage production (Table 4.1), leaf litter production would be most likely affected by changes in tree physiology (Vogt et al. 1986). In addition, the a priori detection limits for differences in foliage litter among years and between sites were much lower than with the wood and the miscellaneous litter fraction (Table 4.2), and so would be a more sensitive indicator of possible ELF effects.

Litterfall weight by species differed between the antenna and control sites due to different species composition at each site (see Chapter 1). Leaf litter at the antenna site had a higher proportion of red maple and bigtooth aspen than at the control site. Conversely, the control site had a much higher mass of northern red oak litter. Total leaf litterfall weight, however, was very similar at both sites over eight years of study, averaging 324 g/m^2 at the antenna site and 345 g/m^2 at the control site, even though considerable paper birch mortality occurred on the control in 1991 and 1992. This is well within the normal range of litterfall for temperate deciduous forests (Bray and Gorman 1964, Crow 1974, Grigal and Grizzard 1975, Boerner 1984, Vogt et al. 1986). Our analysis ELF EM field effects on litterfall of individual tree species produced results similar to that for total leaf litterfall. Consequently, only the results of the total leaf litterfall analysis will be discussed here. More details on litterfall from individual tree species were presented in the annual ELF reports (e.g. Mroz et al. 1993).

Covariate analysis using stand and environmental variables that affect stand production rates measured prior to antenna operation was used to reduce litter fall variability among years, and improve detection limits between the antenna and control site. Total leaf litterfall weight was weakly but significantly correlated to several climate variables. The number of air temperature degree days between August 16 and September 15 (ATD) had the highest correlation with litterfall ($r = -19$) and was used as a covariate in the ANCOVA. Analysis of variance without covariates showed significant differences ($p<0.05$) in total leaf litterfall between the antenna and control sites in 1986 and 1990. When ATD was included in the analysis as a covariate, site differences were found in 1986, 1990, and 1991. Any attempt to improve the correlation by adding or combining climatic factors was unsuccessful. See Mroz et al. (1993) for additional information.

Several studies have found better relationships between climatic factors and deciduous leaf litterfall by using data on a regional or latitudinal basis (Bray and Gorman 1964, Vogt et. al 1986). Kouki and Hokkonen (1992) describe a site-specific model which utilizes early spring and mid-summer monthly temperatures to predict needle litterfall in Scots pine ('*Pinus sylvestris*). They also cite several other studies that predict needle litterfall using temperature factors with various degrees of success. However, we are not aware of any work that has developed site-specific relationships between deciduous leaf litterfall and on-site climatic factors.

Table 4.1 **Significance levels from the split plot analysis of covariance for litter components: 1985 - 1992**

Factor	**Foliage**	**Wood**	**Miscellaneous**
		-----------p values----------	
Site	0.925	0.058	0.191
Years	0.000	0.000	0.000
Site x Years	0.085	0.000	0.195

Table 4.2. Detection limits of litter component weights between treatment sites and among years: 1985-1992.*

Litter Component	**Sites**		**Years**		**Year X Site**	
	g/m^2	%	g/m^2	%	g/m^2	%
Foliage	57.5	17.2	25.3	7.6	35.8	10.7
Wood	18.5	32.4	20.7	36.3	46.5	65.9
Miscellaneous	23.8	45.2	17.9	34.0	24.7	47.4

*The detection limits given are for differences at p=0.05 on covariate adjusted means.

Magnetic flux density was significantly correlated to litterfall weight (r= -.33) and was then added into the ANCOVA along with ATD. The significant site differences found in 1986 and 1990 still remained. However, significant site differences were now also found in 1988 and 1992 (Fig. 4.1). These occurred at various levels of EM exposure, from low-level testing (0.31 mG) in 1986 to full-power operation (7.97 mG) in 1992. But the antenna power varied in a similar manner for years where no significant differences in litterfall weight were found between the sites. No consistent pattern of significant site differences was found relative to the operation of the ELF antenna system. Consequently,it seems unlikely that a cause-and-effect relationship existed between the ELF magnetic flux density and litterfall weight.

Litterfall Nutrients

Total amounts of nutrients returned to the soil by leaf litter on each site reflect differences in both litter weight and nutrient concentrations (Table 4.3). Similar amounts of nutrient additions have been reported for leaf litter on other northern hardwood sites (Gosz *et al.* 1972; Cotrufo 1977). Average foliar nutrient concentrations for combined and individual tree species showed considerable variability between the antenna and control sites, but none were significantly different (Table 4.4 and 4.5).

ANCOVA using climatic and soil factors as covariates (Table 4.6) was used to explain variation in litterfall nutrient concentration. Significant site x year interactions for leaf litter, either composited or for individual tree species, could not be removed by covariate analyses (see Mroz et al. 1993). Multiple range tests (SNK) were performed on these adjusted means to evaluate whether nutrient concentrations had changed in response to ELF antenna operation starting in 1989. These results showed that in all cases significant litter nutrient concentration differences existed between the antenna and control sites prior to antenna operation, and were not altered by exposure to ELF fields.

As a further test of possible ELF antenna effects, covariate analyses were run using both environmental measurements and the ELF field exposure data for 1989, 1990, and 1991 (Mroz et al. 1993). The inclusion of the various ELF field values did not alter or remove the site x year interactions found for litter nutrient concentrations. Since most leaf litter year x site detection levels are below twenty percent of the mean (Mroz et al. 1993), these results indicate that differences in litter nutrient concentrations between the antenna and the control site are not attributable to low-level ELF fields generated since 1989.

Red Oak Foliage

Nutrient concentrations of red oak foliage during the growing season generally showed little differences between the antenna and the control sites (Table 4.7). Results from

Figure 4.1. Leaf litterfall weight and magnetic flux density. (Observed means)

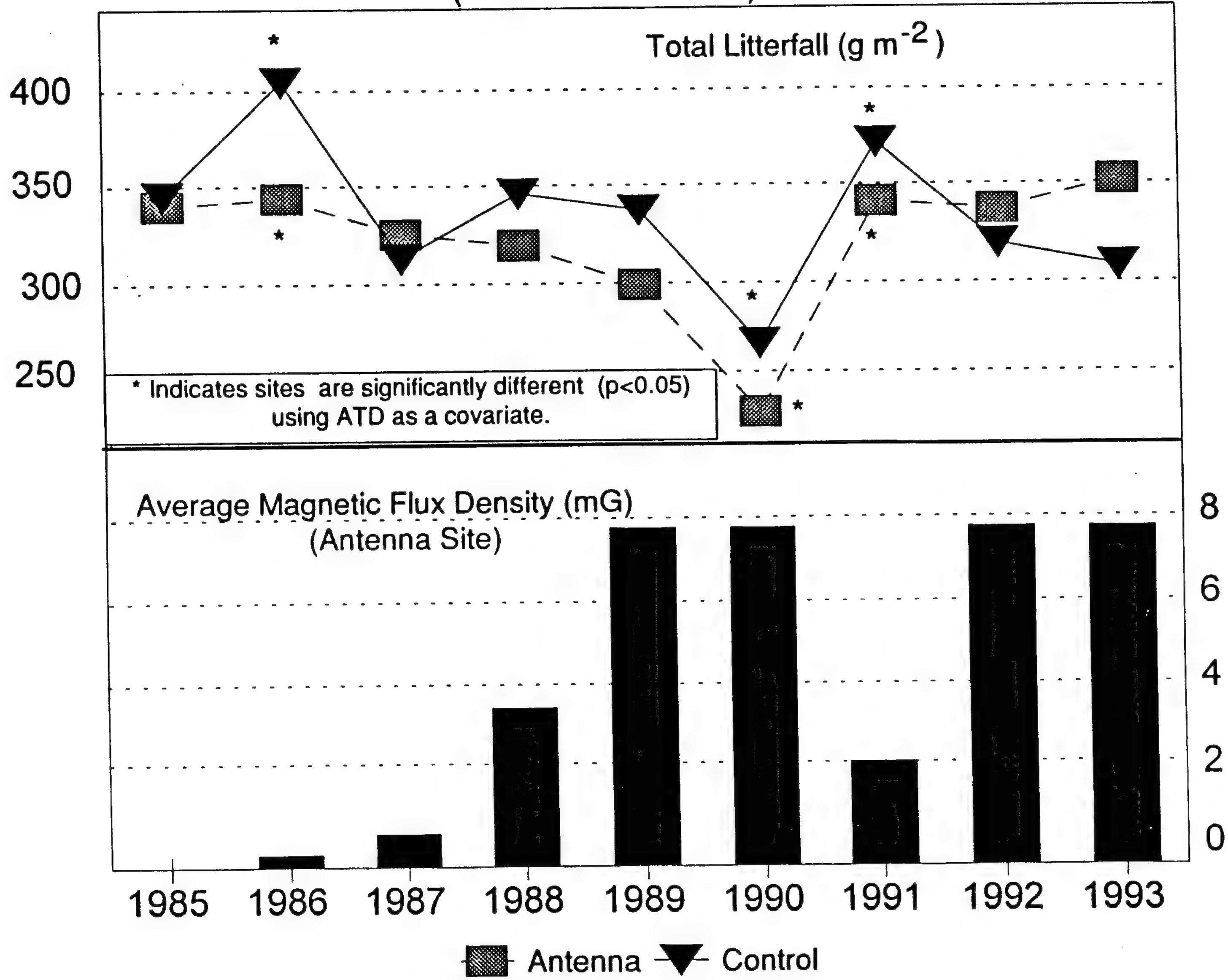


Table 4.3. Average nutrient content of leaf litterfall at the antenna and control sites: 1985-1992

	Antenna	Control
	(kg/ha)	
N	23.5	24.1
P	4.6	6.1
K	11.4	14.6
Ca	37.8	41.9
Mg	5.8	5.9

Values in rows denoted by different letters are significantly different at the p=0.05 level.

Table 4.4. Average nutrient concentrations of leaf litter on the antenna and control sites: 1985-1992

	Antenna	Control
	(%)	
N	0.72 (0.13)	0.70 (0.10)
P	0.14 (0.03)	0.18 (0.07)
K	0.35 (0.08)	0.42 (0.07)
Ca	1.16 (0.21)	1.19 (0.20)
Mg	0.18 (0.03)	0.17 (0.02)

Numbers in parentheses are standard deviations.

Table 4.5. Average nutrient concentrations of tree leaf litter on the antenna and control sites: 1985-1992

	Antenna	Control
	---------------(%)---------------	
Northern Red Oak		
N	0.73 (0.14)	0.66 (0.08)
P	0.13 (0.02)	0.17 (0.08)
K	0.33 (0.07)	0.40 (0.06)
Ca	1.06 (0.18)	1.11 (0.18)
Mg	0.12 (0.01)	0.15 (0.02)
Paper Birch		
N	0.83 (0.14)	0.81 (0.10)
P	0.17 (0.05)	0.18 (0.03)
K	0.42 (0.08)	0.54 (0.13)
Ca	1.48 (0.23)	1.30 (0.28)
Mg	0.27 (0.04)	0.28 (0.04)
Big Toothed Aspen		
N	0.81 (0.11)	0.73 (0.13)
P	0.13 (0.06)	0.15 (0.05)
K	0.38 (0.11)	0.50 (0.11)
Ca	1.42 (0.27)	1.59 (0.30)
Mg	0.27 (0.03)	0.22 (0.03)
Red Maple		
N	0.48 (0.06)	0.49 (0.09)
P	0.17 (0.04)	0.18 (0.02)
K	0.27 (0.09)	0.36 (0.10)
Ca	1.12 (0.14)	1.27 (0.18)
Mg	0.19 (0.02)	0.20 (0.03)

Numbers in parentheses are standard deviations.

Table 4.6. Climatic and soil nutrient variables used as covariates in ANCOVA for litter nutrient analysis. (Values in parentheses are significant ($p<0.05$) correlation coefficents with litterfall nutrients.)

Ca	Mg	K	N	P
ATMXO(-.35)	NKG(-.21)	CAPPM(.40)	NPPM(-.22)	KPPM(.49)
	KKG(-.16)	MGPPM(.48)	ATMXS(-30)	ATMNO(.45)
	ATMXS(-.51)	ATDRTO(.35)		CAKG(.32)

Soil nutrient covariates:

CAKG = Soil calcium (kg ha^{-1})
KPPM = Soil potassium (kg ha^{-1})
CAPPM = Soil calcium (mg kg^{-1})
NKG = Soil nitrogen (kg ha^{-1})
MGPPM = Soil magnesium (mg kg^{-1})
NPPM = Soil nitrogen (mg kg^{-1})
KKG = Soil potassium (kg ha^{-1})

Climatic covariates

ATMXS = Average daily maximum air temperature in September
ATMXO = Average daily maximum air temperature in October
ATMNO = Average daily minimum air temperature in October
ATDRTO = Cumulative air temperature degree days from January 1 to the end of October

Table 4.7. Northern Red Oak foliage nutrient concentration for antenna and control sites: 1985 to 1991

	Antenna	Control
	-------(%)-------	-------(%)-------
N	2.06	2.04
P	0.21	0.21
K	0.87	0.98
Ca	0.72	0.72
Mg	0.15	0.15

covariate analyses using soil and climatic data showed there were no significant site x year interactions for any foliage nutrient (Table 4.8). Nutrient detection limits for red oak foliage were quite good (under fifteen percent) for all but P (Mroz et al. 1993). An analysis of variance was also conducted on red oak leaf weights from the antenna and the control sites. No significant site, month, year, and diameter interactions were found. Consequently, red oak nutrient concentrations during the growing season were not related to operation of the ELF antenna.

Red Pine Foliage

Similar to red oak leaves during the growing season, one-year old red pine foliage showed little differences among the three study sites (Table 4.9). Results from the ANOVA tests and the detection limits associated with the SNK tests (8-17%) showed that site-by-year interactions were significant only for N and Mg in 1988 prior to ELF antenna transmissions (Figure 4.2). These initial site nutrient differences are likely related to the residual effects of plantation establishment on nutrient availability, differences in soil amelioration rates, or differing acclimation rates of seedlings at the three sites.

A further analysis of red pine nutrient concentrations in relation to 76hz magnetic fields on the ELF test sites and the control indicated significant ELF field correlations with foliar Ca and Mg levels (Table 4.10). However, these foliar nutrient and magnetic flux density relationships were not consistent at both the ground and the antenna sites. These magnetic field-related differences in red pine nutrient concentrations may be caused by independent site characteristics which vary spatially in a manner similar to the ELF fields at a given site. Overall, these results were similar to the red oak leaves, indicating that red pine nutrient concentrations had not been altered by ELF antenna operation.

Table 4.8. Results of covariate analyses for differences in red oak leaf nutrient concentration: 1985-1992

	N (1)*	P (2)	K (3)	Ca (4)	Mg (5)
		----------------p values	----------------	----------------	
Site	.024	.093	.050	.235	.206
Year	.000	.531	.035	.002	.000
Year x Site	.113	.959	.849	.282	.412

* Covariates used:

1 Average daily maximum air temperature, average daily maximum soil temperature at 5 cm, average daily maximum soil moisture at 10 cm, average daily maximum soil temperature 10 cm

2 Average daily soil temperature degree days at 10 cm running total, average daily minimum soil moisture at 5 cm, average daily maximum soil moisture at 10 cm

3 Average daily minimum soil temperature at 5 cm, average daily maximum air temperature, average daily and daily minmum soil moisture at 10 cm

4 Average daily maximum air temperature, average daily soil temperature at 10 cm

5 Average daily maximum air temperature, average daily minimun soil moisture at 10 cm, average daily soil temperature degree days at 10 cm

Table 4.9. Red pine seedling foliage nutrient concentrations at the three ELF study sites: 1986 to 1993

	Antenna	Ground	Control
		(%)	
N	1.16	1.11	1.12
P	0.14	0.13	0.13
K	0.40	0.40	0.40
Ca	0.25	0.25	0.26
Mg	0.09	0.09	0.09

Table 4.10. Correlation coefficients and significance levels associated with 76 hz magnetic flux densities and foliar nutrient concentrations for the ground and antenna sites :1990-1993

	Ground	Antenna
N	-0.111 (p=0.418)	0.189 (p=0.166)
P*	-0.057 (p=0.715)	-0.002 (p=0.989)
K	0.017 (p=0.900)	0.267 (p=.049)
Ca	0.367 (p=0.006)	0.197 (p=0.149)
Mg	0.257 (p=0.058)	0.494 (p<0.001)

*Phosphorus used 1991-1993 data

FIGURE 4.2a RED PINE FOLIAR NITROGEN CONCENTRATIONS 1986-1993

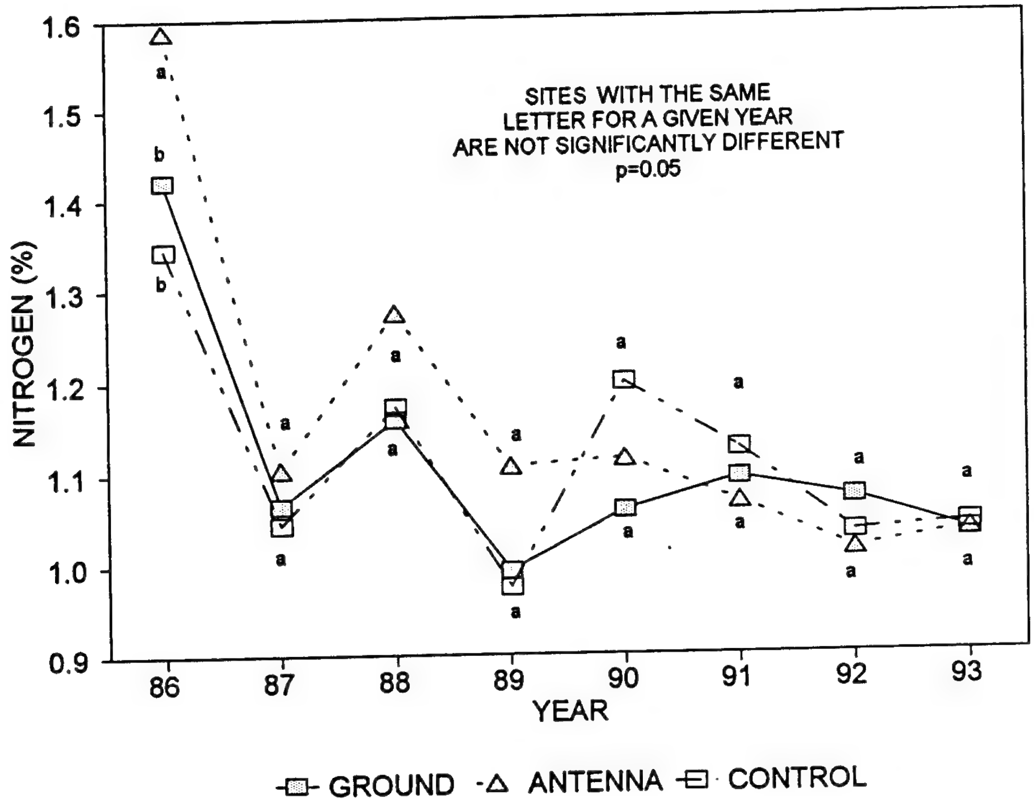
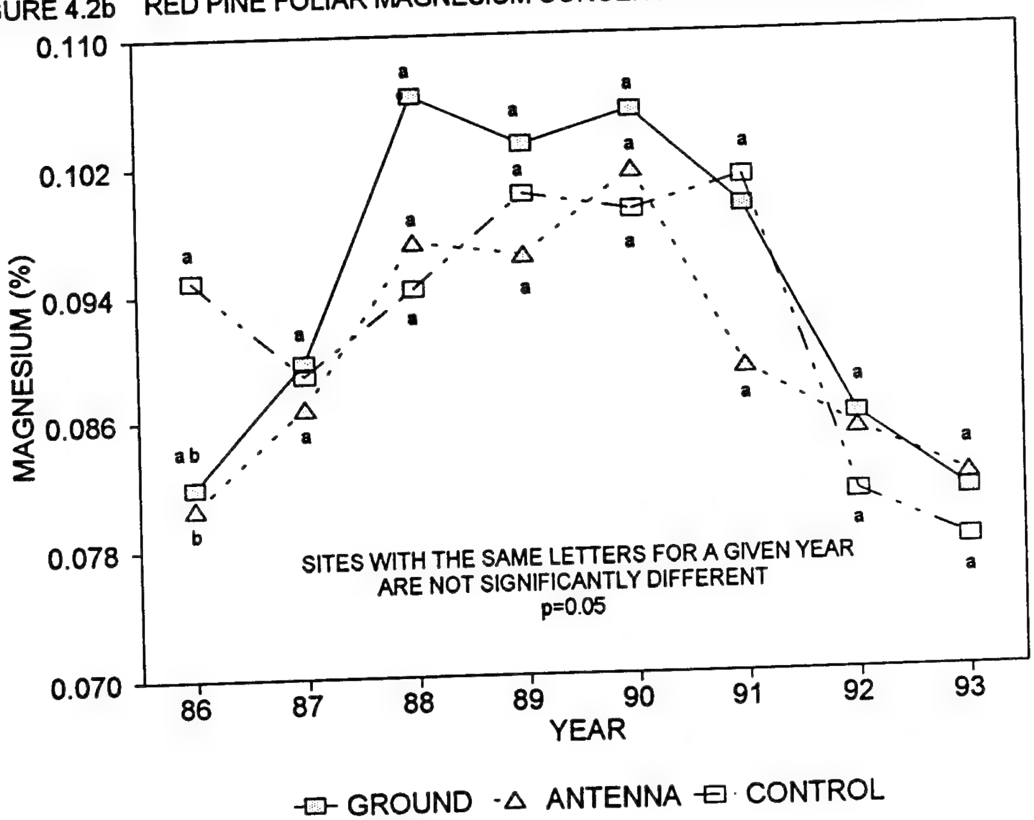


FIGURE 4.2b RED PINE FOLIAR MAGNESIUM CONCENTRATIONS 1986-1993



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CHAPTER 5

THE EFFECTS OF 76 HZ ELECTROMAGNETIC FIELDS ON MYCORRHIZAL ASSOCIATIONS OF RED PINE (PINUS RESINOSA AIT.)

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ABSTRACT

Mycorrhizal fungi are obligate symbionts, directly dependent on a plant's physiology for their health. Mycorrhizae of plantation red pine (*Pinus resinosa* Ait.) seedlings were chosen as sensitive biological indicators to reflect perturbations which might be caused by ELF EM fields. Monthly (May-October) measurements of numbers of mycorrhizal root tips were taken on three sites (antenna, ground, and control) from 1985-1993. Mycorrhizae were categorized into morphological types produced by different fungal associations on red pine seedlings. Changes in both the frequency of occurrence for different mycorrhizal types and the total numbers of mycorrhizae per seedling were quantified for analysis both within and among years as well as among sites. Data for analysis was expressed as the total number of mycorrhizae per gram of seedling dry root mass. Although significant site by year interactions were initially determined, differences were explained using total precipitation and days of precipitation events greater than 0.10 cm. Findings indicate that mycorrhizal associations on red pine seedlings were not affected by ELF EM fields.

INTRODUCTION

Background

Mycorrhizae are symbiotic structures representing a finely balanced physiological relationship between tree roots and specialized fungi, providing mutual benefit to both partners of the symbiosis. Mycorrhizal fungi are obligately bound to their host requiring photosynthate from the tree for their energy source. In return, the matrix of fungal mycelium from colonized roots, which permeates the forest floor and mineral soil, provides the host tree with minerals and water more efficiently than without its fungal partner. Thus, mycorrhizal formation and numbers are sensitive to factors affecting either the fungus component or the host plant component.

Mycorrhizae have been selected in other studies as sensitive indicators of subtle environmental changes. Studies have been designed to monitor the effects of acid rain on forest ecosystems using mycorrhizal numbers as the parameter of assessment (Reich *et al.* 1985, Shafer *et al.* 1985, Stroo and Alexander 1985, Dighton and Skeffington 1987). Others have examined mycorrhizae and how they were affected by ozone and air pollution (Kowalski 1987, Reich *et al.* 1985, Mejstrik and Cudlin 1987), and heavy metal buildup in soils (Jones and Hutchinson 1986).

Numerous studies have dealt with the effects of ELF EM fields on root growth processes (Robertson et al. 1981; Inoue et al. 1985; Brayman et al.

1987; Kato 1988; Brayman and Miller 1989; Kato et. al. 1989; Rabold et al. 1989; Kato 1990; Rathore 1990). However, most of these studies have been done in the laboratory and used aqueous solutions to grow plant roots. No studies (to date) have assessed the effects of ELF EM fields on mycorrhizal associations. Extremely low frequency EM fields could detectably alter the more discriminating mycorrhizal fungus component. Mycorrhizae data may also be used to substantiate responses seen in other measures of tree productivity.

Hypotheses and Test Procedures

The main scientific hypothesis tested was:

> HO: There are no differences in population densities of different types of mycorrhizae on red pine seedlings before or after the ELF EM antenna becomes activated.

The specific null hypothesis tested over all years was:

> HO: There is no difference in the number of different types of mycorrhizal root tips on red pine seedlings before or after the ELF EM antenna becomes activated.

Other changes that could occur are reflected by possible alternative hypotheses such as; 1) shifts in population species composition and 2) changes in the character of mycorrhizal morphology type. Although many types of mycorrhizae occur on these sites, this study has examined only ectomycorrhizal fungi formed on red pine root systems.

METHODS

Sampling Methods

In conjunction with work on tree productivity, fifteen red pine seedlings per site (five per plot per site) were sampled monthly from May to October during years 1985-1993. To retrieve mycorrhizae-bearing roots, the seedling's root system was excavated using a shovel, producing a soil sample between 10-50 cm in diameter and 10-25 cm deep. Sampling areas were enlarged as seedlings grew. Red pine seedling fine (< 3mm) roots were extracted from this sample (in the field) to obtain approximately 30 to 60 cm of total root length. Lateral roots from each seedling with adherent soil were wrapped tightly in individual plastic bags, placed in a cooler and transported to the laboratory where they were refrigerated. Within two to three days, roots were rinsed first in a small volume of distilled water (1:1 water to root/soil volume), then washed gently in tap water, placed in a fresh volume of tap water and refrigerated. Approximately 0.25 g roots (fresh weight) per sample were removed at this time for actinomycete enumeration (Bruhn et al. 1993). Counting mycorrhizal tips was begun immediately with counts completed within two weeks of field sampling.

A shallow pan containing a small amount of water was used during the root sectioning and counting operation. The roots were sectioned into 3 cm segments. Thirty segments were selected at random to total 90 cm of lateral roots per seedling. As each 3 cm root segment was counted, its

diameter and number of mycorrhizae were recorded. A mycorrhiza was defined as a terminal mycorrhizal root tip at least 1.0 mm in length; hence a mature dichotomously branched mycorrhizal root tip was tallied as two mycorrhizae.

Mycorrhizae were counted by morphological type. Three types of morphological roots were delineated. The Type 3 ranged in color from a tan to a deep red-brown color and was formed primarily by *Thelephora terrestris* and/or *Laccaria laccata* (*sensu lato*). The second type, Type 5, had a nearly black to deep jet-black color due to colonization by *Cenococcum graniforme*, an abundant mycorrhizal fungus in the original and surrounding hardwood forests. The third type, Type 6, was white to tan in color, floccose in form, and is presumably colonized by *Boletus, Hebeloma, Paxillus* or *Suillus* spp. Though slight color variations occur within morphological types, all fit within the grouping of these three main types. A dissecting microscope was used to distinguish mycorrhizal types. Morphology types were tallied separately and then totaled for each seedling. Non-mycorrhizal root tips were easily distinguishable as white root tips composed entirely of plant tissue, obviously lacking a fungal component.

Upon completion of counting, segments were collectively (by seedling) dried at $60^{O}C$ to constant mass, then weighed. Mycorrhizal counts for each 90 cm of roots were expressed as number of mycorrhizal tips per gram (o.d.w.) of dry root. This measure has been used in other root studies examining mycorrhizae dynamics in forest ecosystems (Harvey *et al.* 1987).

Statistical and Test Procedures

Three sites (ground, antenna, and control) were used for this portion of the study. Red pine seedlings were outplanted in June, 1984 at a 1 m x 1 m spacing. Although red pine seedlings were outplanted in 1984, data from that year will not be used in the analysis. Reasons for this are: 1) nursery seedlings are small and planting shock is known to have a significant effect on seedling root systems and 2) ambient weather and soil data were not available for 1984.

A nested analysis of variance was used to test site, year, and site-by-year interactions. The error term used to test site differences was plot within site. The error term used to test yearly differences was month within year, and the error term used to test site-by-year interactions was year by plot within site. These error terms were used because of the occurrence of unequal variances in the total number of mycorrhizae per gram of dry root among plots and among months. The following assumptions were made: 1) site differences were mainly due to plot differences, 2) yearly differences were mainly due to monthly variations, and 3) site-by-year differences were mainly due to plot variations within site by year. Detection limits calculated with three years of data prior to the fully operational ELF Antenna (1985, 1986, 1987) indicated that an overall difference of approximately 15 to 25 percent would be necessary to identify a significant difference among years and among site-by-year interactions.

Analysis of covariance was used to explain any differences in mycorrhizal numbers due to precipitation amounts. Precipitation variables were averaged for the month prior to the sampling date. Correlation analysis was used to choose the "best" covariate(s). A significance level of $p=0.05$ with

the Student Newman Keuls's Multiple Range Test was used to detect significant differences among means.

RESULTS AND DISCUSSION

From 1985 non-mycorrhizal root tips declined until 1987 when none were observed for the final month at the ground and control sites, and for the last four months at the antenna site. Less than three non-mycorrhizal roots per year have been counted since 1988. This sudden decline in uncolonized root tips was likely a function of seedling maturation, and indicated that the seedlings were becoming fully adapted to native soil microflora.

Type 3 mycorrhizae were the major mycorrhizal type on seedling root systems at all sites (Figures 5.1 and 5.2). Significant monthly and yearly fluctuations did occur on all sites.

Figure 5.1: Monthly and yearly comparisons of the total number of mycorrhizal root tips (ECM) per gram of dry root.

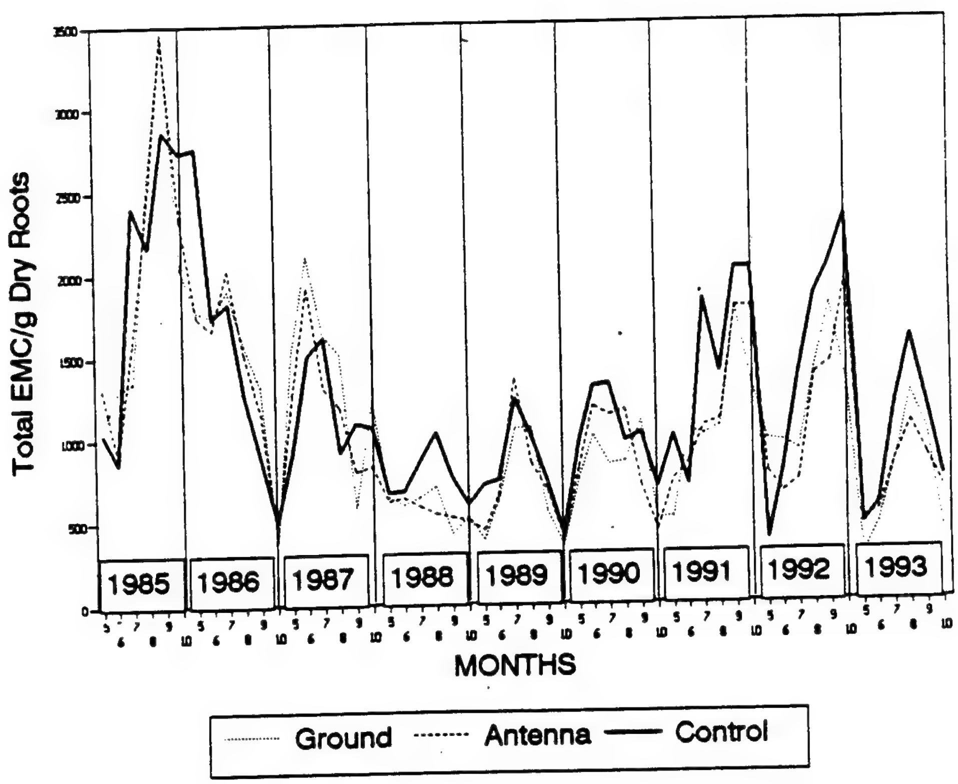
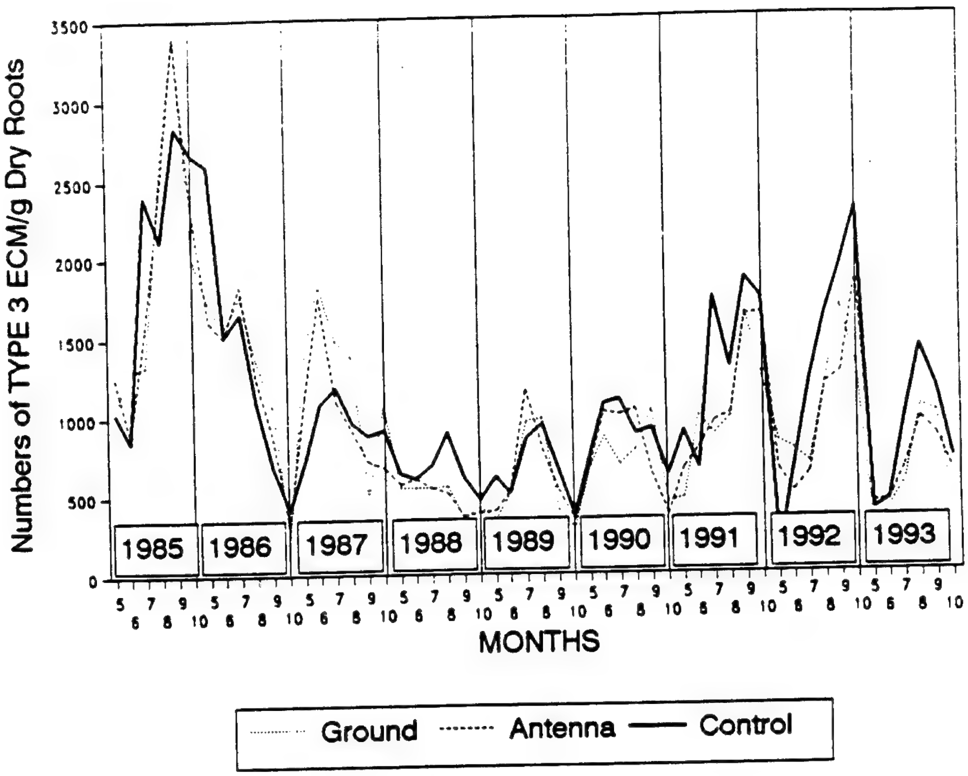


Figure 5.2: Monthly and yearly comparisons of the number of Type 3 mycorrhizal root tips (ECM) per gram of dry root.



Type 5 mycorrhizae were significantly less abundant than Type 3 mycorrhizae (Figure 5.3; note scale change on Y axis from Figures 5.1 and 5.2). As Type 3 mycorrhizae, significant monthly and yearly fluctuations were also observed (Figure 5.3).

Type 6 mycorrhizae were the least common type encountered for all study sites. Type 6 mycorrhizae were first observed in late 1984 on very few seedlings. In 1985 and 1986, no seedlings were found with Type 6 mycorrhizae. In 1987, the occurrence of Type 6 mycorrhizae were infrequent and sporadic; they were found on all sites (but not all months). In 1988, numbers of Type 6 mycorrhizae were similar to the 1987. In 1989, however, numbers of Type 6 mycorrhizae declined with only the Control and Ground sites having similar numbers in May and the Control and Antenna sites having similar numbers in July. In 1990, numbers of Type 6 mycorrhizae significantly declined except for September when numbers increased on the Ground site. Due to the lack of adequate information on Type 6 mycorrhizae, it was not used in subsequent analyses.

Analysis of variance (ANOVA) was performed with eight years of data (1985-1992) to detect differences among sites and among years, and their interactions, on total mycorrhizae per gram of dry root. Without covariates, mycorrhizal numbers were significantly different ($p<0.05$) among sites, years, and site-by-year interactions (Table 5.1). After the ELF antenna became fully operational, mean numbers of of Total and Type 3 mycorrhizae were significantly less on the antenna and ground sites than on the control site (Figure 5.4A).

Figure 5.3: Monthly and yearly comparisons of the number of Type 5 mycorrhizal root tips (ECM) per gram of dry root.

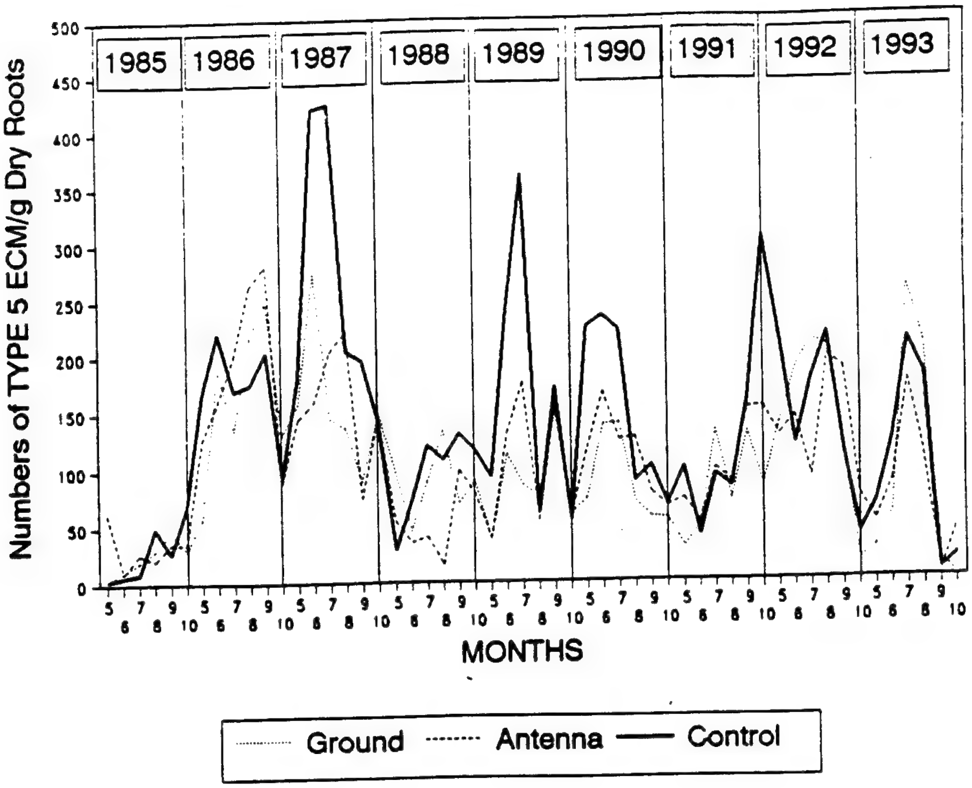
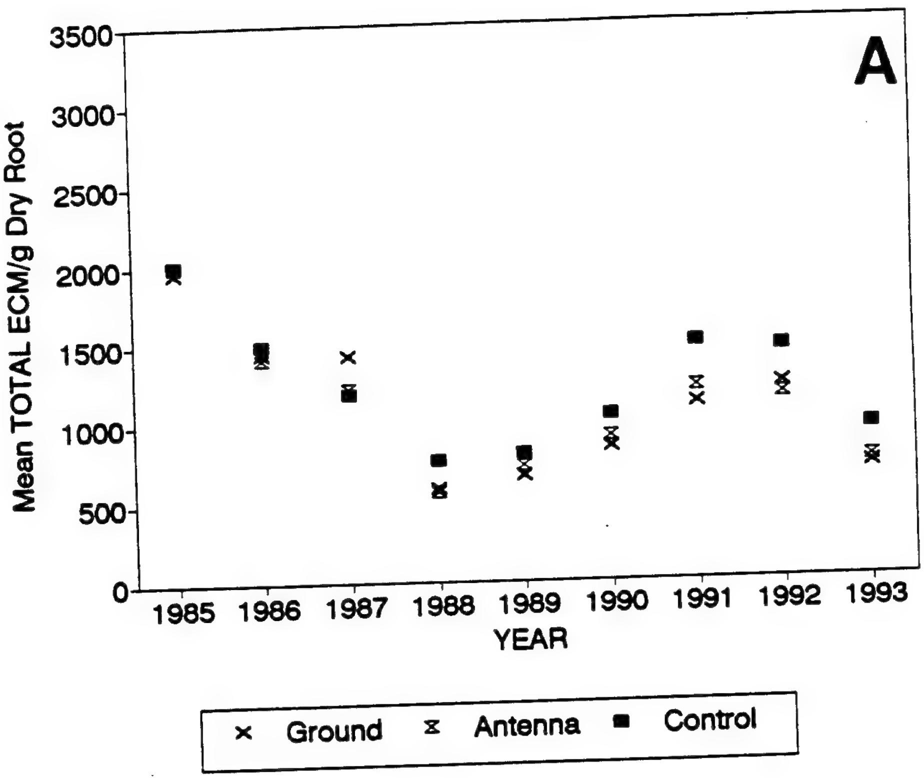


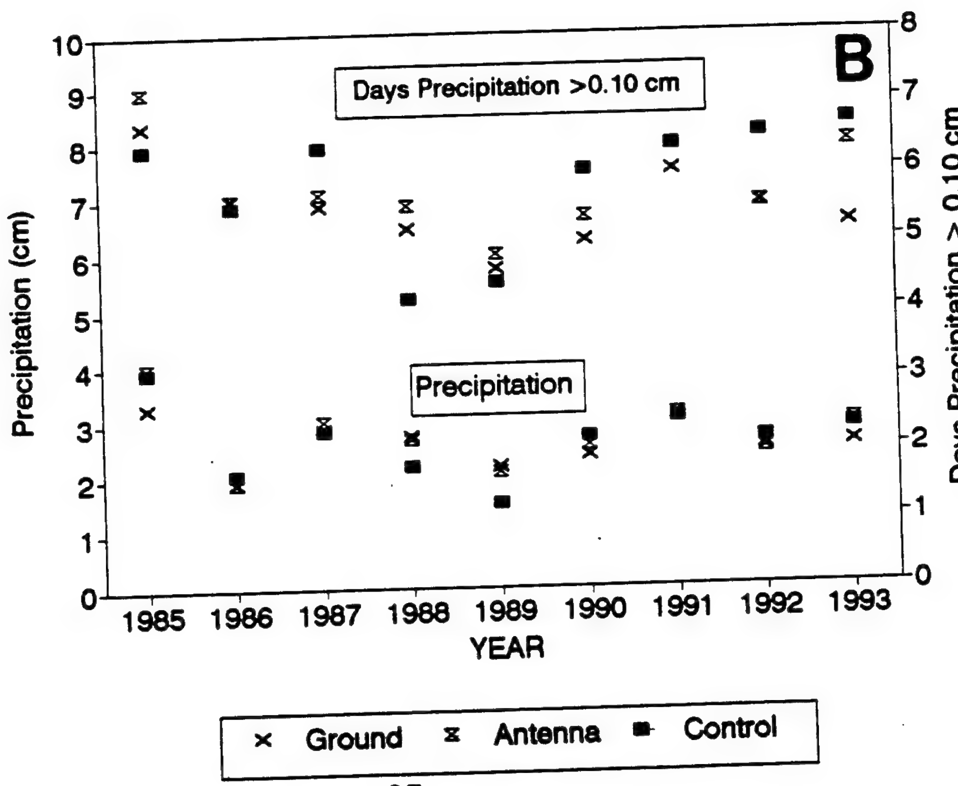
Table 5.1. Comparison of p values (significance of F) for total mycorrhizae per gram of seedling root data (1985 through 1993 after multiple analysis of covariance (ANCOVA) using some of the highly correlated ($p < .001$) ambient parameters.

COVARIATE	SITE	YEAR	YEAR x SITE
No Covariate	.053	.000	.049
PRC.01	.343	.001	.054
PRC.10	.043	.002	.082
PRCTOT	.555	.002	.062
PRCTOT + PRC.10	.680	.002	.222

Covariate analysis was then used to explain the differences in numbers of total mycorrhizae per gram dry root among sites, years, year-by-site interactions by taking into account the variation in precipitation conditions. Mean precipitation values represent a period of approximately 30 days prior to each mycorrhizae sampling date. Number of days precipitation greater

Figure 5.4: Year by site comparisons of (A) total number of mycorrhizal root tips per gram of dry root and (B) total precipitation and number of days precipitation greater than 0.10 cm.





than 0.01 cm (PRC.01) and 0.10 cm (PRC.10), and total precipitation (cm) (PRCTOT) were significantly ($p < 0.01$) correlated to total and Type 3 mycorrhizal numbers (Figure 5.4B). However, correlation coefficients were low ($r = 0.12$) for all three variables.

To test whether the addition of a covariate explained yearly differences in mycorrhizal numbers, analysis of covariance (ANCOVA) was performed with the eight years of collected data. Table 5.1 lists probability (p) values (significance of the F statistic) after analysis of covariance, using the three precipitation variables. The addition of two variables, total precipitation and the number of days precipitation was greater than 0.10 cm, was also tested in the analysis. Although p values for site factors and site and year interactions changed (increased in most cases), yearly differences could not be explained. Significantly fewer numbers of mycorrhizae occurred in years 1988, 1989, and 1990 compared with years 1985, 1986, 1987, 1991, and 1992. Except for 1991, differences may be due to the acclimation of seedlings to their habitat.

Precipitation most likely affects seedling root growth and mycorrhizal development because of the effect of drought on mycorrhizal fungi . It is believed that some fungi have the ability to enhance root processes during droughty periods (Allen 1991). However, there are some fungi that do not enhance water uptake in dry periods (Allen 1991). On these sites, mycorrhizal numbers increased with increased precipitation.

The ELF Antenna system has been operational since the fall of 1989. If there were ELF effects on mycorrhizae numbers, the most important source of variation attributable to these effects would be the site by year interaction. If there was an effect, numbers of mycorrhizae from years 1990, 1991, and 1992 on the Antenna and/or Ground site(s) would be significantly different than the numbers on the Control site or from prior years information. This was not the case. Results indicate ectomycorrhizal symbiosis between tree roots and fungi have not been affected by ELF EM fields.

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CHAPTER 6

EFFECTS OF 76 HZ ELECTROMAGNETIC FIELDS ON STARFLOWER, *TRIENTALIS BOREALIS* RAF. PHENOLOGY

Margaret R. Gale and Peter J. Cattelino

ABSTRACT

Coordinated timing or the phenology of herbaceous plant production is extremely important for continued growth and health. Significant changes in phenological processes have been used as indicators of plants under stress. Thus, the phenology of a small herbaceous species, starflower (*Trientalis borealis* Raf.), was monitored to assess the effects of 76 Hz electromagnetic fields (ELF) on the herbaceous plant community within hardwood stands. Phenological changes in budbreak, flowering, fruiting, leaf senescence and leaf and stem expansion were monitored during the growing seasons of 1985 to 1992. Research sites were established near the overhead ELF Antenna and at a Control site located approximately 50 km from the Antenna site. Climatic and stand characteristics were also measured from 1985-1992 and used as covariates to explain significant differences in leaf expansion, leaf size (area, length, and width), and stem length between sites, and among years and site-by-year interactions.

Significant site-by-year interactions were observed for julian dates of initial budbreak and leafout. These differences were attributed to the initiation of sampling and not to ELF. Significant variation in stem expansion, leaf length and width expansion, and leaf area expansion, between the antenna and the control site, was explained using microsite basal areas, soil temperature degree days running total at 10 cm, maximum solar radiation, and precipitation. These covariates also explained significant variations in leaf area expansions among site-by-year interactions, but significant site-by-year differences for stem length, leaf length, and leaf width expansion were evident. These differences did not, however, statistically reflect ELF EM effects but possible differences in climate, handling, and other factors not measured in this study. Significant differences in population means among the antenna and control sites were observed before and after full operation of ELF EM fields.

INTRODUCTION

Background

Phenological events, or the coordinated timing of certain morphological processes, are important phytometers of plants under stress. Events, such as stem elongation, bud break, leaf expansion, flowering, fruiting and leaf senescence have been used in the past to monitor and assess a plant's response to factors such as climate and soils. Morphological characteristics, such as leaf area, stem length, number of buds, number of leaves, number of flowers, and number of fruit have also been used to monitor a plant's response to these factors. By combining both phenological and morphological information, researchers have obtained a

better understanding of the potential changes plants will exhibit in response to perturbations.

In the past, considerable work had been done to assess the effects of electric fields on plant growth with varying results (Gardner et al. 1975; Miller et al. 1976; Miller et al., 1983; Adamec et al., 1989; Krizaj and Valencie, 1989; Peteiro-Cartelle and Cabezas-Cerrato, 1989). However, all of these studies were done in a laboratory in which field strengths were controlled without interference from other woody plants; plants were also grown in aqueous solutions, perlite, or on petri dishes,not in soil. Very few studies have assessed the effect of electric fields on phenological plant processes. Rosenthal (1975) determined enhanced responses in stem and root lengths of sunflower seeds immediately after germination. Rosenthal (1976) also studied general vegetation patterns adjacent to the Wisconsin ELF EM antenna; no differences were observed.

In 1983, the US Navy installed an Extremely Low Frequency (ELF) Communication System in Michigan's Upper Peninsula. Research sites were established near an overhead ELF EM antenna and at a control site located approximately 50 km from the antenna site. In 1986, low level testing of the ELF EM system began; full operation (24 hours/day) was begun in September, 1989 (Note: intermittent operation of the ELF EM antenna at 44 and 80 Hz did occur during the 1989 growing season; our sampling dates ranged from late April until mid August).

The majority of ecosystems along the ELF EM antenna are forested, consisting mainly of northern hardwoods ecosystems. These ecosystems are extremely important resources for plant diversity and for wood products. Starflower is an important herbaceous species in many northern, forested ecosystems and is especially important in hardwood ecosystems of the North Central Region. Phenophases of starflower have been well documented in northern Wisconsin by Anderson and Loucks (1973) and in Canada by Helenurm and Barrett (1987). Because of prior information on phenophases and morphological characteristics of starflower and because we considered starflower to be sensitive to site disturbances, it was chosen as an indicator of ecosystem responses to 76 Hz electromagnetic fields.

The objectives of this study were to: 1) describe and document specific changes in the phenological events and morphological characteristics of *Trientalis borealis* Raf. prior to, and during operational use of the ELF EM antenna and 2) use these data to test hypotheses of possible changes in phenological processes and morphological characteristics due to ELF EM fields.

Hypotheses and Test Procedures

The main scientific hypothesis tested was:

> HO: There is no difference the onset of budbreak, flowering, fruiting, and leaf and stem expansion of *Trientalis borealis* Raf. between the Antenna and the Control sites within a year.

The specific null hypothesis tested over all years was:

> HO: There is no difference in the onset of flowering, fruiting, and leaf and stem expansion of *Trientalis borealis* Raf. before and after the ELF EM antenna becomes operational.

Morphological characteristics (number of buds, flowers, fruit, and leaves) were also analyzed within the context of these hypotheses. Ambient characteristics, described in Chapter 2, within each year were used as covariates to explain significant differences in phenological characteristics of leaf expansion, leaf size (area, length, and width), and stem length between sites, and among years and site-by-year interactions.

METHODS

Sampling Methods

Data were collected on two sites (antenna and control sites) from late April-early May until mid-August from 1985 until 1992. Each site was sampled twice a week early in the growing season to delineate leaf expansion with greater precision. After full leaf expansion, each site was sampled once a week until mid-August. Parameters measured per plant for each observation period included stem length, length and width of the largest leaf, and number of leaves, buds, flowers, fruit, yellow leaves (leaves senescing), and brown leaves.

To ensure an adequate representation of starflower phenophases, a minimum sample size of 200 individual plants per site was maintained for each observation period during leaf expansion. To achieve this goal, a 40 m transect was permanently marked and subsequently divided into 1 m^2 subplots. Individual plants within each subplot were numbered and tagged until a normal distribution of mean stem length was attained. Stem length was used as the response variable for this determination because it is a prime indicator of a herbaceous plant's potential sexual productivity. A normal distribution of stem length ensured an adequate representation of the population for analysis of variance techniques. The number of meter square subplots, required to obtain a minimum sample size of 200 plants, varied between the antenna and control site and among weeks sampled. To reduce bias in choosing the 200th individual, all individual plants were tagged and measured in the subplot where the 200th plant occurred, hence sample size was unequal across sampling days. This sampling method was maintained for each individual plant until tagged individuals began to die or were eaten. Thereafter, observations were taken only on the remaining tagged individuals. Maximum leaf area was estimated for each plant by 1) taking the largest leaves on 15 randomly sampled plants off the herbaceous reserves at each observation period from 1986-1992, 2) measuring leaf length, leaf width and leaf area on these 15 samples, and 3) developing regression equations for leaf area (dependent variable) using leaf length and width as independent variables

To determine if handling had a significant effect on stem length, leaf length, and leaf width on both the control and the antenna sites, three permanent plots (1 m^2) were randomly established in 1989 on each site approximately 1 m from the sampled transect at varying distances along the transect. All

plants within the "unhandled" plots were measured on one occasion per year (the last measurement period for each year). Care was taken to ensure the least amount of handling occurred to plants on the "unhandled" plots.

Analysis of covariance (ANCOVA) was used to determine if climatic and microsite characteristics could be used to explain differences in stem expansion (cm/time period), leaf expansion (cm/time period), and leaf area expansion (cm^2/time period) between sites (antenna vs control), years, and site-by-year interactions (Table 6.1). Student-Newman-Keuls multiple comparison test was used to group like means.

Because of evident microplot (subplot) variation due to differences in overstory characteristics along the sampling transect, additional information on basal area and canopy coverage of woody species over each subplot was measured in 1989 (before full operation of the antenna). Basal area by species and total basal area were estimated for each subplot using a 10 factor prism. Canopy coverage on the ground and at 4.5 feet was measured using a spherical densiometer.

Table 6.1: Analysis of Covariance table for stem, leaf length, leaf width, and leaf area expansion.

Source of Variation	df	SS	MS	F
Year	7	SS_y	MS_y	MS_y/MS_{e1}
Covariates	#	SS_{cy}	MS_c	MS_c/MS_{e1}
Error 1 (P/Y)	40-#	SS_{e1}	MS_{e1}	
Site	1	SS_s	MS_s	MS_s/MS_{e2}
Site by Year	7	SS_{sy}	MS_{sy}	MS_{sy}/MS_{e2}
Covariates	#	SS_{cs}	MS_{cs}	MS_{cs}/Ms_{e2}
Error 2 (SxP/Y)	40-#	SS_{e2}	MS_{e2}	

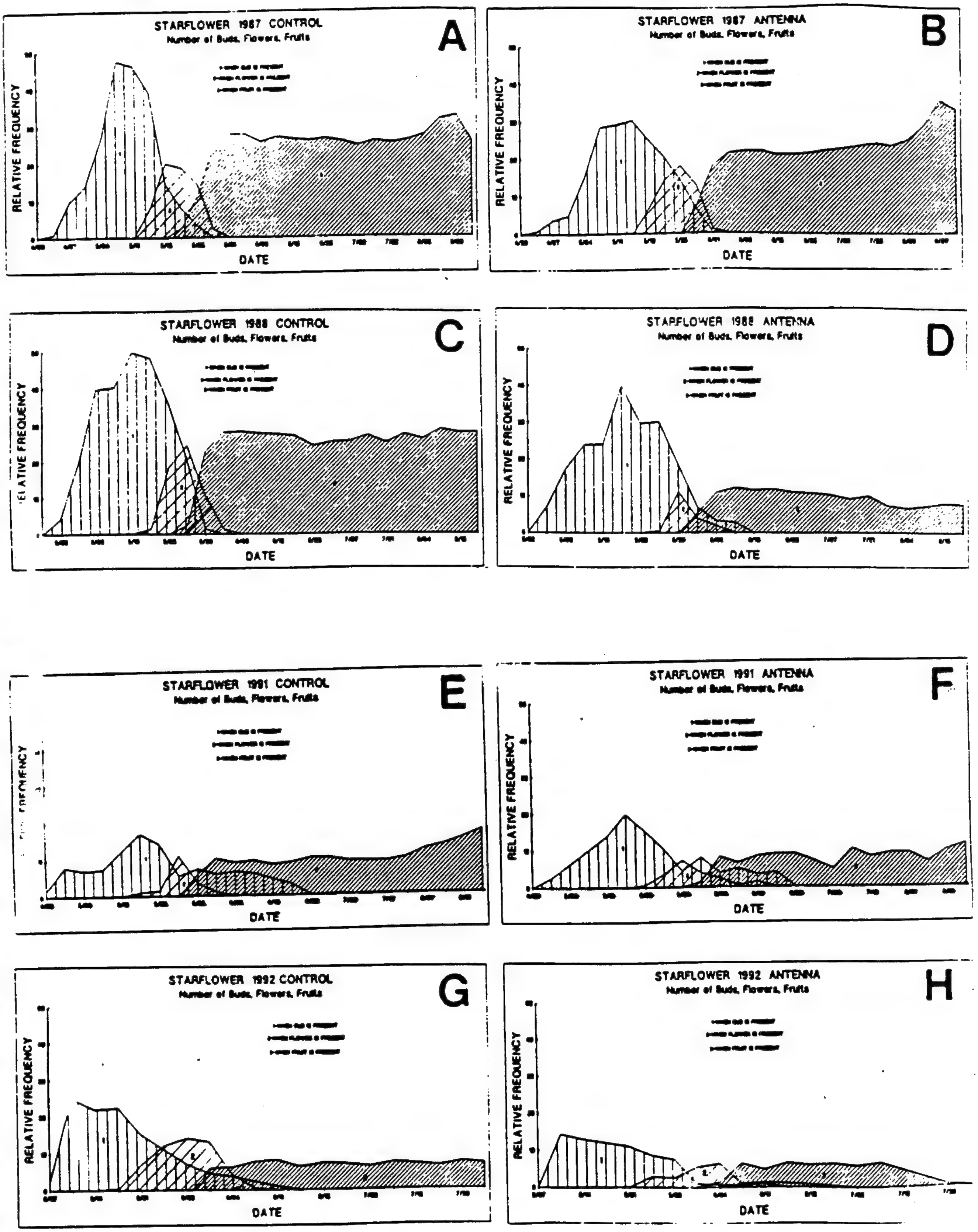
RESULTS AND DISCUSSION

Phenological Characteristics

There were no significant site-by-year interactions ($p = 0.05$) for the initiation dates for flowering, fruiting, senescing leaves, and browning leaves, indicating that ELF EM fields after the 1989 growing season had no effect on the timing of these phenological events. Significant site-by-year interactions ($p < 0.01$) were determined for julian dates of initial leafout and budbreak. These differences were due to fluctuations in the beginning sampling date for each year. Site differences in julian dates for these variables were not detected after the ELF EM antenna became operational.

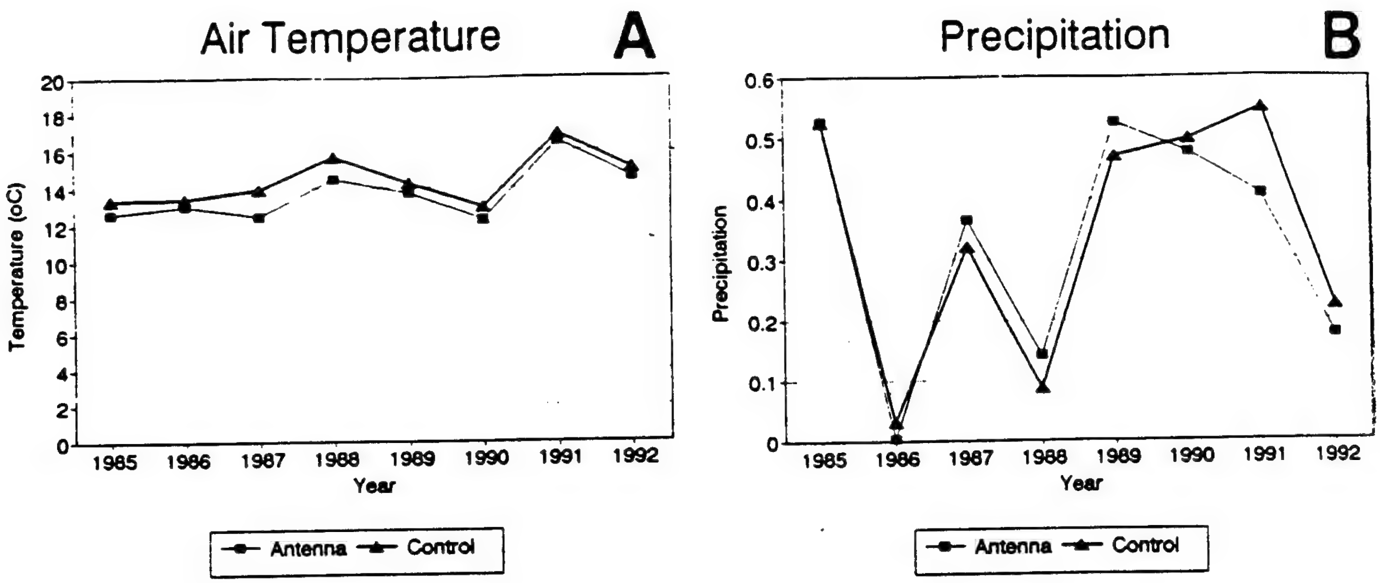
Prior to full-power antenna operation (1985-1989), flowering and fruiting on both sites began when the previous event (e.g., budbreak and flowering, respectively) was at its maximum (Figures 6.1A-6.1D). Note: only represented years for data collected in 1987, 1988 (before full operation of

Figure 6.1: Comparison of the relative frequency and proportion of plants with one or more buds, flowers, and fruit by sampling date on the control site 1987 (A), antenna site 1987 (B), control site 1988 (C), antenna site 1988 (D), control site 1991 (E), antenna site 1991 (F), control site 1992 (G), and antenna site (1992).



the ELF EM antenna), 1991, and 1992 (after full operation of the ELF EM antenna) have been included. However, in 1992, the population of starflower growing on the antenna initiated flowering after the peak of budbreak; fruiting began before the peak of flowering (Figure 6.1D). Reasons for the changes observed in 1992 are unclear. In 1991, timing of flowering and fruiting on the antenna site was similar to patterns in 1989, 1988, 1987, 1986, and 1985. Climatic conditions in 1991 (higher temperatures and precipitation amounts) may be the reasons for similar patterns in 1991 (Figures 6.2A-6.2B). Relatively lower temperatures and higher precipitation amounts occurred in 1990.

Figure 6.2: Comparison of mean air temperature (A) and precipitation (B) on the antenna and control sites. Note: mean values for air temperatures and precipitation are not the same as presented in Chapter 2. Values reflect starflower sampling times from late April until mid August.



Over all years, the number of plants with buds, flowering, and fruiting were significantly lower in 1986, 1987, and 1988 on the antenna site than on the control site (Figures 6.3, 6.4, and 6.5). Reasons for this are unknown. No significant differences between the antenna site and control site ($p = 0.05$) in the number of plants flowering and fruiting were observed after 1988. The number of plants with buds were significantly higher on the control site in 1989 and 1990; however these differences were not evident after 1990 (Figures 6.3C and 6.3D). No significant differences in site by year interactions of initiation brown or yellow leaves were detected. These analyses indicate no significant effects on phenological processes due to ELF EM fields.

Figure 6.3: Relative frequency for number of plants with one or more buds by sampling date on the control and the antenna sites for 1987 (A), 1988 (B), 1991 (C), 1992 (D).

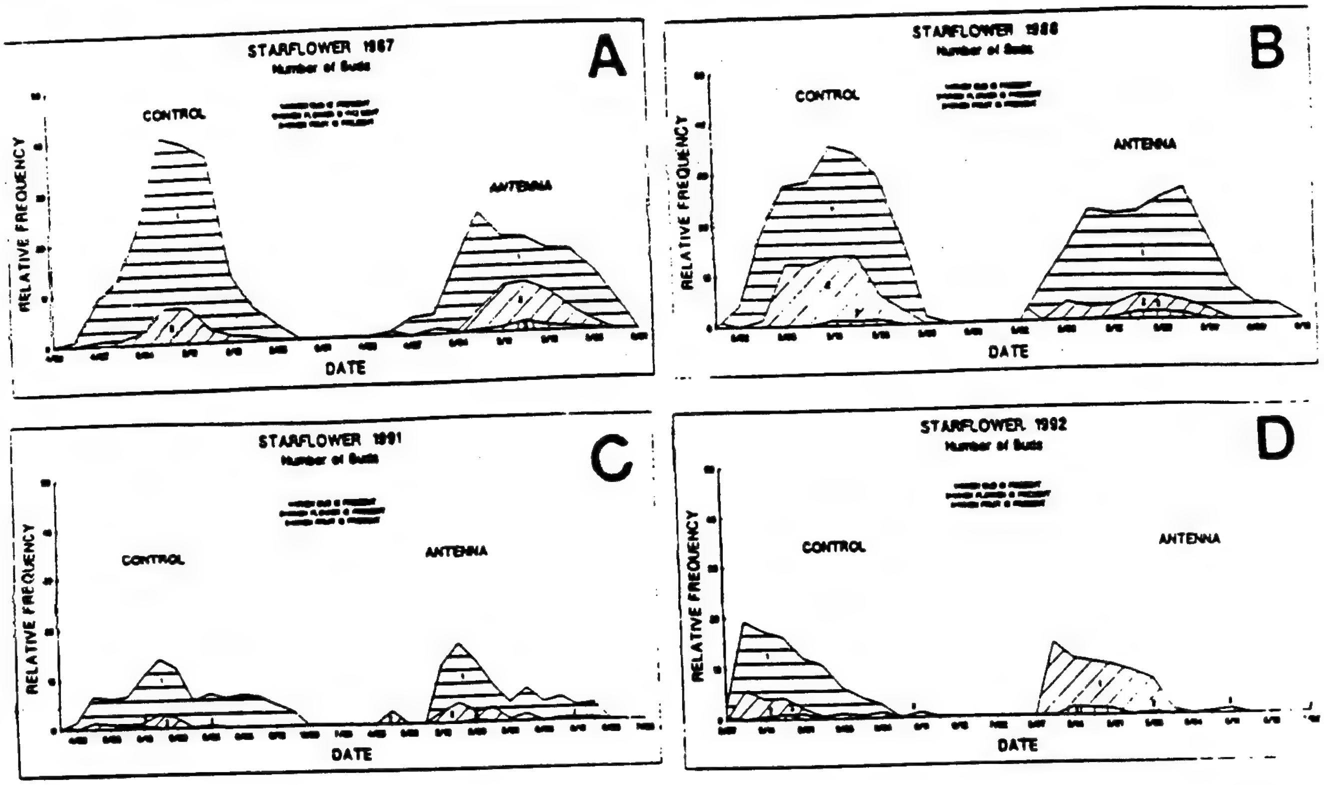


Figure 6.4: Relative frequency for number of plants with one or more flowers by sampling date on the antenna site and the control site for 1987 (A), 1988 (B), 1991 (C), 1992 (D).

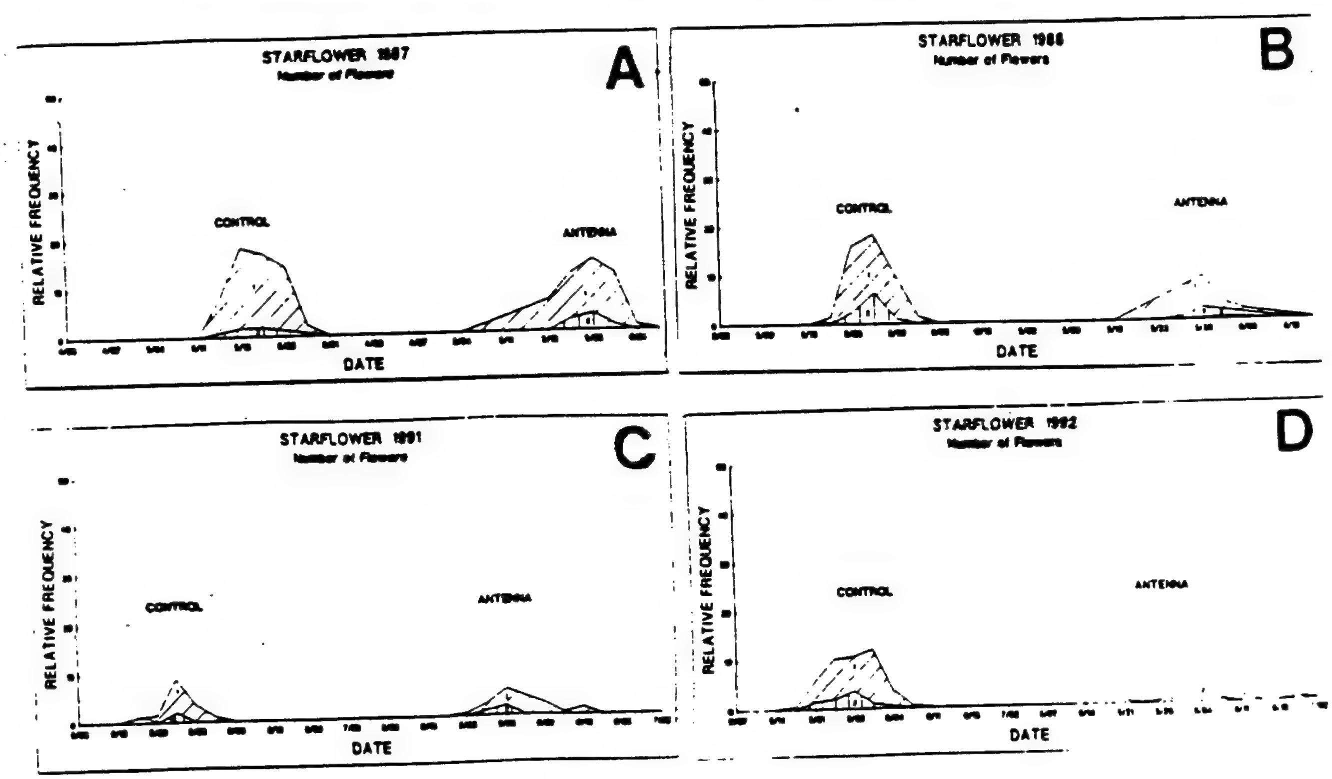
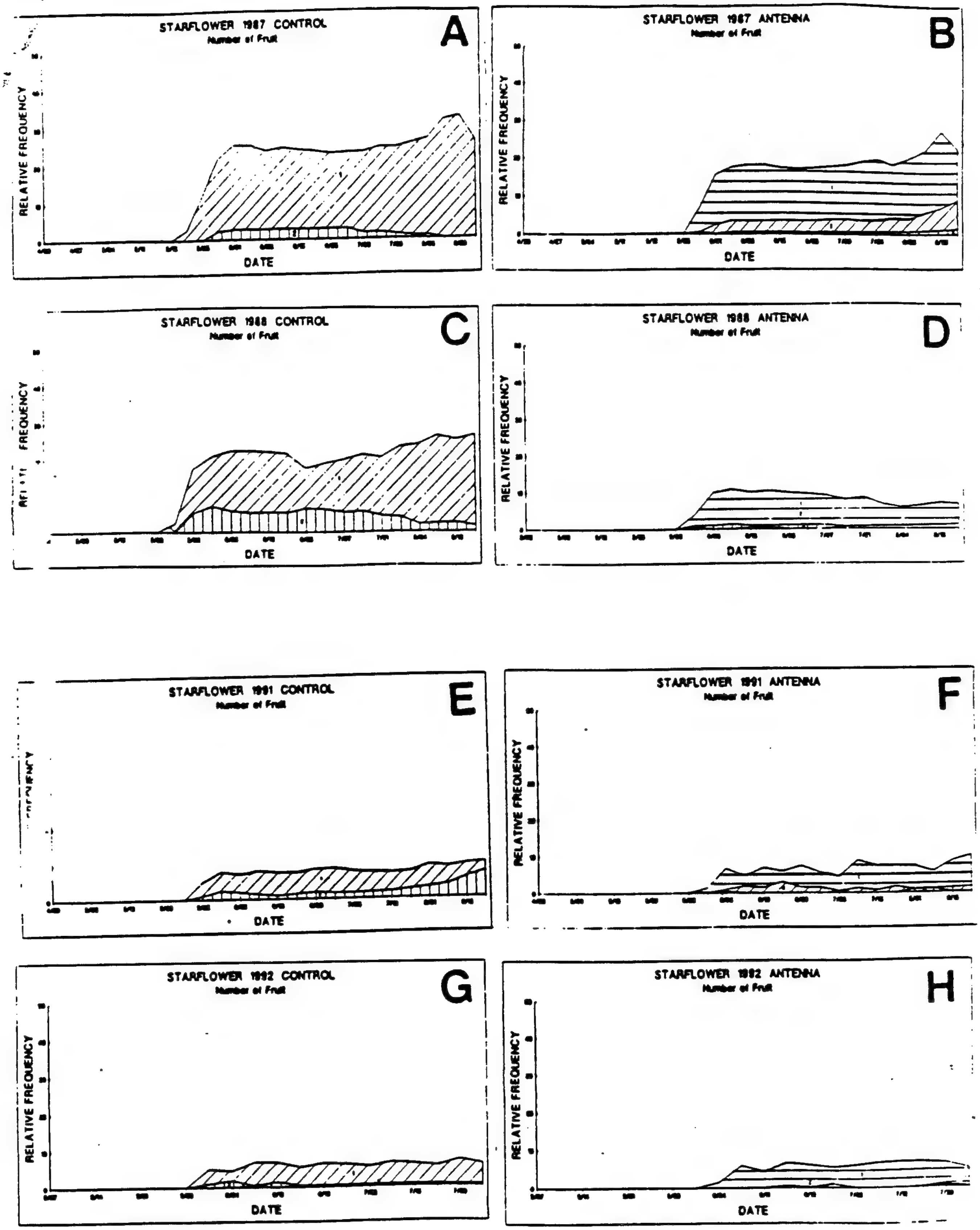


Figure 6.5: Relative frequency for number of plants with one or more fruit by sampling date on the control site 1987 (A), 1988 (C), 1991 (E), 1992 (G); and the antenna site in 1987 (B), 1988 (D), 1991 (F), 1992 (H).



Using ANOVA, stem length, leaf length, leaf width, and leaf area expansion on the antenna site were significantly different (p <0.01) from the control site (Table 6.2A). Year and site-by-year interactions were also significantly different (Table 6.2A).

Table 6.2: Results of ANCOVA (p values) to determine significant differences in stem expansion (STEM), leaf length expansion (LGTH), leaf width (LWTH) expansion, and leaf area expansion (LAREA) between sites, years, and site by years.

A) No Covariates

Source of Variation	STEM	LGTH	LWTH	LAREA
Year	0.00	0.00	0.00	0.00
Site	0.00	0.00	0.00	0.00
Site by Year	0.00	0.00	0.00	0.00

B) Covariates for Stem Length (STEM), Leaf Length (LGTH), Leaf Width (LWTH), and Leaf Area (LAREA). Bigtooth Aspen Basal Area (BTABA) + Northern Red Oak Basal Area (NROBA) + Natural Log (Soil Temperature Degree Days Running Total at 10 cm)/BTABA + Natural Log (Soil Temperature Degree days Running Total at 10 cm)/NROBA + Maximum Solar Radiation/NROBA + Precipitation/NROBA.

Source of Variation	STEM	LGTH	LWTH	LAREA
Year	0.00	0.00	0.00	0.00
Site	0.81	0.99	0.77	0.87
Site by Year	0.00	0.03	0.03	0.69

Prior to ANCOVA, scatterplots of soil temperature degree days running total versus the response variables indicated that the variation in the response variables increased with soil temperature (non-constant variance). This problem was solved by taking the natural log of soil temperature degree days running total. Correlations were then calculated between starflower measurements and climatic and microsite variables. The variables most highly correlated to stem length, leaf area, leaf length, and leaf width expansion were 1) maximum solar radiation (SOLMX) (r=-0.14, -0.38, -0.37, -0.40, respectively), 2) natural log of soil temperature degree days running total at 10 cm (LST10DRT) (r=0.17, 0.53, 0.58, and 0.66, respectively), 3) bigtooth aspen basal area (BTABA) (r=0.22, 0.30, 0.29, and 0.25, respectively), and 4) northern red oak basal area (NROBA) (r= -0.20, -0.30, -0.29, and -0.26, respectively).

Interactions between climate variables and microsite variables were also highly correlated to stem length, leaf area, leaf length, and leaf width expansion (ie., LST10DRT/BTABA (r=-0.12, -0.21, -0.18, -0.16,

respectively), and LST10DRT/NROBA (r=0.16, 0.30, 0.30, 0.24, respectively) SOLMX/BTABA (r= -0.20, -0.30, -0.32, -0.30, respectively)). Although not highly correlated to leaf area, leaf length, and leaf width expansion, the interaction SOLMX/NROBA (r=-0.04, -0.03, 0.01, -0.07, respectively) was used as a covariate to explain the greater component of northern red oak trees on the control site than on the antenna site. Precipitation and its corresponding interaction with basal area estimates were not as highly correlated with stem length, leaf area, leaf length, leaf width as other ambient data (absolute r values ranged from 0.02 to 0.16) but added significant amounts of explained variation in the response variables when used in covariate analysis (Table 6.2B).

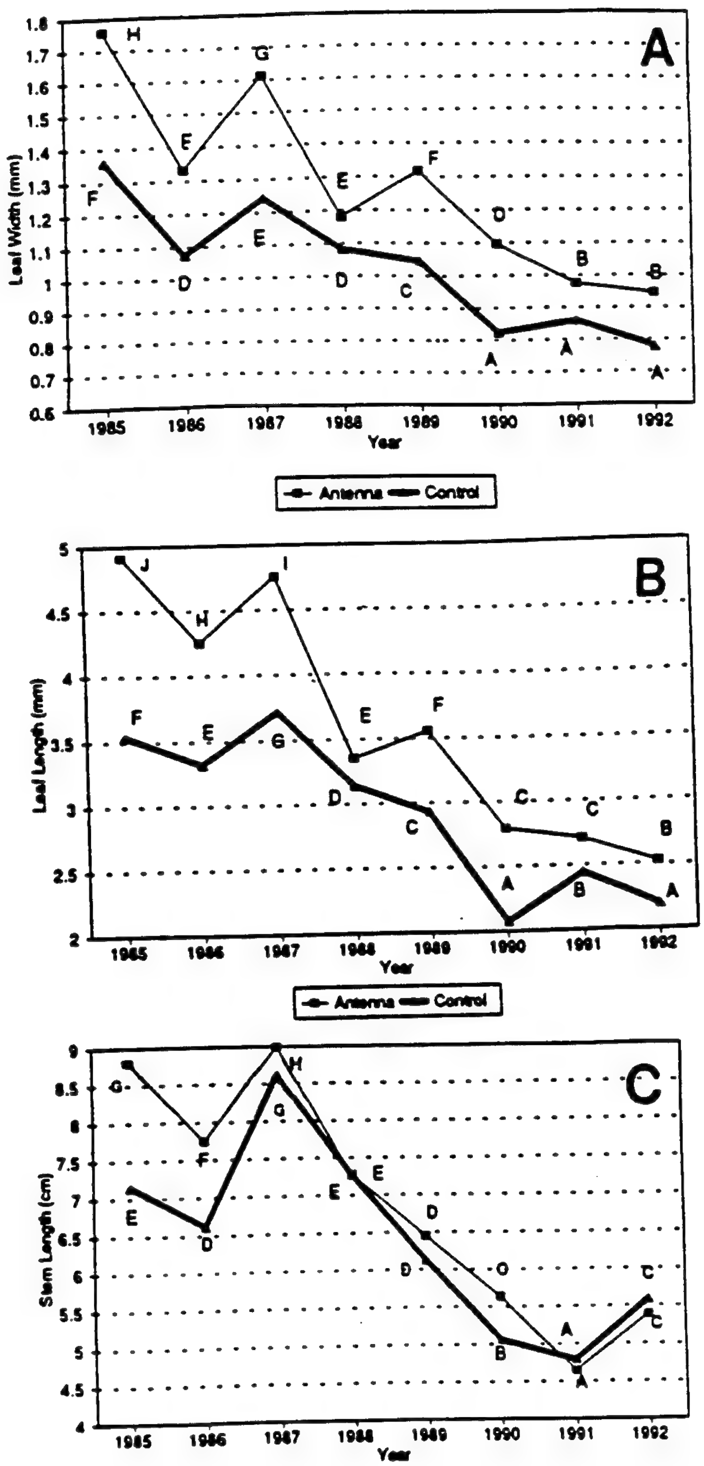
The use of these covariates explained significant amounts of variation in leaf area, leaf length, and leaf width expansion between sites but not among years (Table 6.2B). These covariates also explained significant amounts of variation in site-by-year interactions for leaf area expansion. However, site-by-year interactions for leaf length, leaf width, and stem length expansion were significantly different (Table 6.2B). When individual means for stem length, leaf length, and leaf width were compared, no discernable patterns due to ELF EM effects were observed (Figures 6.6A-6.6C). Mean values for all variables decreased on both the Antenna and the Control site over the eight years of this study (Figures 6.6A-6.6C). Reasons for this are unclear.

A separate study was done to determine if continued handling could have affected the population of plants on these sites. Mean stem lengths, leaf lengths, and leaf widths on both the "handled" plots and the "unhandled" plots on the control site and the antenna site were then statistically compared. In 1989, results indicated that there were no significant decreases ($p > 0.20$) in stem length, leaf length, and leaf width of "handled" plants on both the control site and the antenna site. In 1990 and 1992, similar results were determined. Due to problems in data acquisition, handling data collected in 1991 were lost. In 1989, 1990, and 1992, no significant interactions ($p = 0.05$) were determined among site and handling treatments. Therefore, handling had no significant effect on the above-mentioned variables.

Morphological Characteristics

Observations in the past years suggested a clonal difference between the population of starflower on the antenna site versus the population on the control site. In 1990, starflower plants and soils from each site were collected off the herbaceous transects and reciprocally transplanted on to the other site. Plants were randomly chosen from each site and placed in the same light regime on the other site. Plants were then measured in early September to determine if there were morphological differences between the two sites. In 1990, the transplant study indicated that there was a significant reduction ($p < 0.05$) in the stem length of plants taken from the control and planted on the antenna site versus average stem lengths on the control site. Number of leaves, leaf lengths, and leaf widths were not statistically different between the sites. At this time, there is no explanation for these results. In 1991, none of the transplants could be found on either site, thus this study was not continued in 1992. It is believed that the transplants on both sites did not produce a rhizome at the end of the

Figure 6.6: Comparison of leaf widths (A), leaf lengths (B), and stem lengths (C) for the control versus the antenna site for years 1985-1992.



growing season in 1990. This was probably due to transplant shock and/or other climatic factors.

Using regression analysis, linear equations were fit to observations of leaf area using leaf length and leaf width measured on destructively sampled starflower plants off the herbaceous reserves for each year (1986-1992) on each site (Table 6.3). The independent variable of leaf width x leaf length explained over 98 percent of the variation in leaf area for both sites in 1986, 1987, 1989, 1990, 1991, and 1992. Ninety-two and 96 percent of the variation in leaf areas was explained using the variable leaf width x leaf length for the control and the antenna sites, respectively, in 1988. Higher standard errors occurred with the development of the 1988 curves (Table 6.3).

Table 6.3. Leaf area (LA) equations for each site in each year and for all sites and all years using leaf width (Lw) and leaf length (Ll).

Site (Year)	Equation	$S_{y.x}$[1]
Control Site (1986)	LA = 0.09 + 0.55 (Lw x Ll)	0.20
Control Site (1987)	LA = 0.11 + 0.56 (Lw x Ll)	0.18
Control Site (1988)	LA = 0.40 + 0.52 (Lw x Ll)	0.68
Control Site (1989)	LA = 0.05 +.0.57 (Lw x Ll)	0.18
Control Site (1990)	LA = 0.08 + 0.56 (Lw x Ll)	0.16
Control Site (1991)	LA = 0.13 + 0.56 (Lw x Ll)	0.21
Control Site (1992)	LA = 0.15 + 0.57 (Lw x Ll)	0.22
Antenna Site (1986)	LA = 0.13 + 0.55 (Lw x Ll)	0.26
Antenna Site (1987)	LA = 0.13 + 0.56 (Lw x Ll)	0.34
Antenna Site (1988)	LA = 0.32 + 0.52 (Lw x Ll)	0.60
Antenna Site (1989)	LA = 0.05 + 0.56 (Lw x Ll)	0.24
Antenna Site (1990)	LA = 0.15 + 0.54 (Lw x Ll)	0.37
Antenna Site (1991)	LA = 0.12 + 0.54 (Lw x Ll)	0.35
Antenna Site (1992)	LA = 0.20 + 0.54 (Lw x Ll)	0.28

[1] Standard error of regression

Regression coefficients (intercepts and slopes) were tested to determine if there were significant differences ($p = 0.05$) between sites (antenna vs control), among years, and among site-by-year interactions. In 1992, significant ($p < 0.001$) year and site differences in both the slopes and the intercepts were observed. Intercepts for the antenna and control sites in 1988 were again significantly greater than in 1986, 1987, 1989, 1990, 1991 and 1992; the intercept for 1989 was significantly lower than all other years. Slopes for the antenna and control sites were significantly lower in 1988 than for 1986, 1987, 1989, 1990, 1991, and 1992. These differences may be due to inaccurate leaf sampling techniques. However, these differences indicate no significant effect due to ELF EM fields.

CONCLUSIONS

Differences in phenological events of starflower (bud break, flowering, fruiting, leafout, leaf senscence (yellow and brown)) between the antenna and control sites were not evident after the ELF EM antenna became fully operational (September, 1989). Significant variation in stem expansion, leaf length and width expansion, and leaf area expansion between the antenna and the control site can be explained using microsite basal areas, soil temperature degree days running total at 10 cm, maximum solar radiation, precipitation, and interactions between these variables. These covariates also explained significant variations in leaf area expansions among site-by-year interactions but not for stem length, leaf length, and leaf width expansion. However, differences were not related to ELF EM fields. Our conclusion is that ELF EM fields have not significantly influenced starflower populations on the antenna site.

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APPENDIX A

ELF Electromagnetic Field Site Selection Criteria

ELF Electromagnetic Site Selection Criteria
(Brosh *et. al.* 1985)

Control plots shall be selected at locations where electric fields in soil near the surface of the earth produced by the ELF system are on the average at least one order of magnitude and preferably two orders of magnitude less than those at paired test plots. The same relationship shall exist for magnetic field components between test and control plots. Electric and magnetic fields in air and earth produced by other ELF sources (e.g., power lines) shall not differ by more than one order of magnitude between paired test and control plots, and at test plots should be at least one order of magnitude below the fields produced by the ELF system.

It is also desired that the fields produced by the ELF system at the test sites be at least one order of magnitude higher than the 60 Hz fields (e.g., power lines) at the control sites.

These conditions can also be stated as follows:

(1) $$\frac{T\,(ELF)}{C\,(ELF)} \geq 10$$

(2) $$\frac{T\,(ELF)}{T\,(60)} \geq 10$$

(3) $$\frac{T\,(ELF)}{C\,(60)} \geq 10$$

(4) $$0.1 \leq \frac{T\,(60)}{C\,(60)} \leq 10$$

where: $T\,(ELF)$ = Test site EM field level due to ELF system
$T\,(60)$ = Test site EM field level due to power lines
$C\,(ELF)$ = Control site EM field level due to ELF system
$C\,(60)$ = Control site EM field level due to power lines.

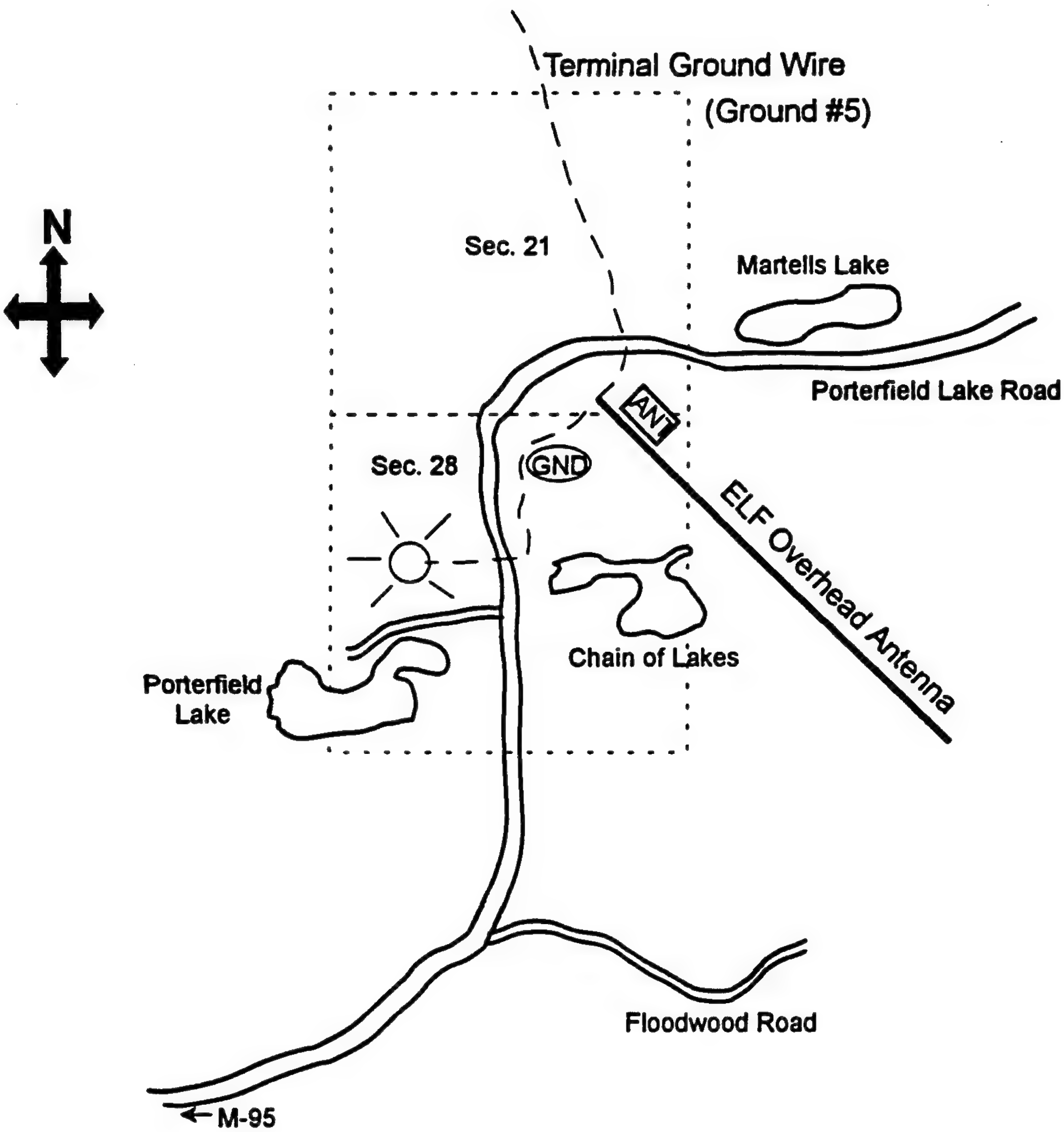
APPENDIX B

Study site location maps and plot configuration of the Herbaceous Plant and Tree Studies

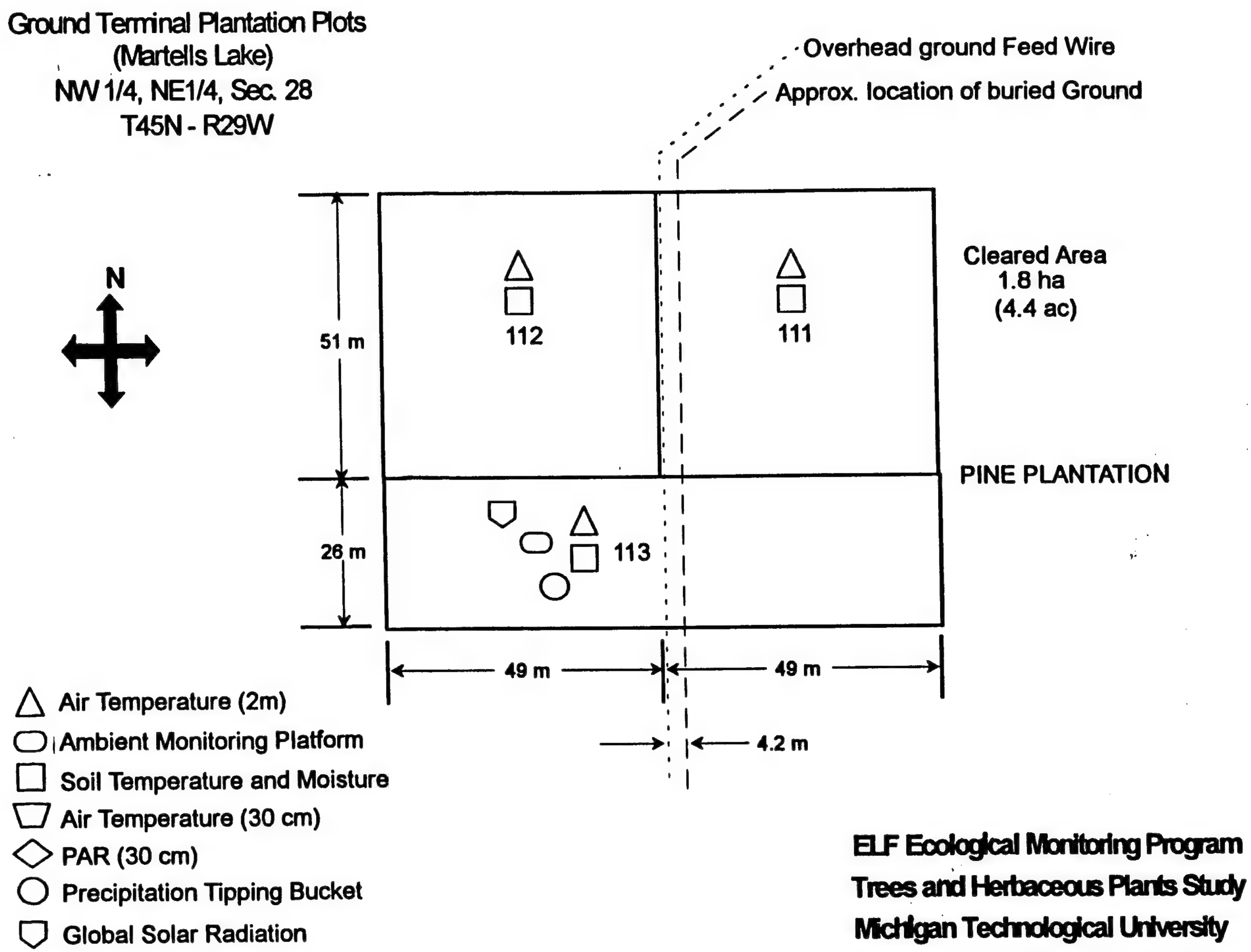
ELF ANTENNA TEST PLOTS

T45N, R29W
(Martell's Lake)

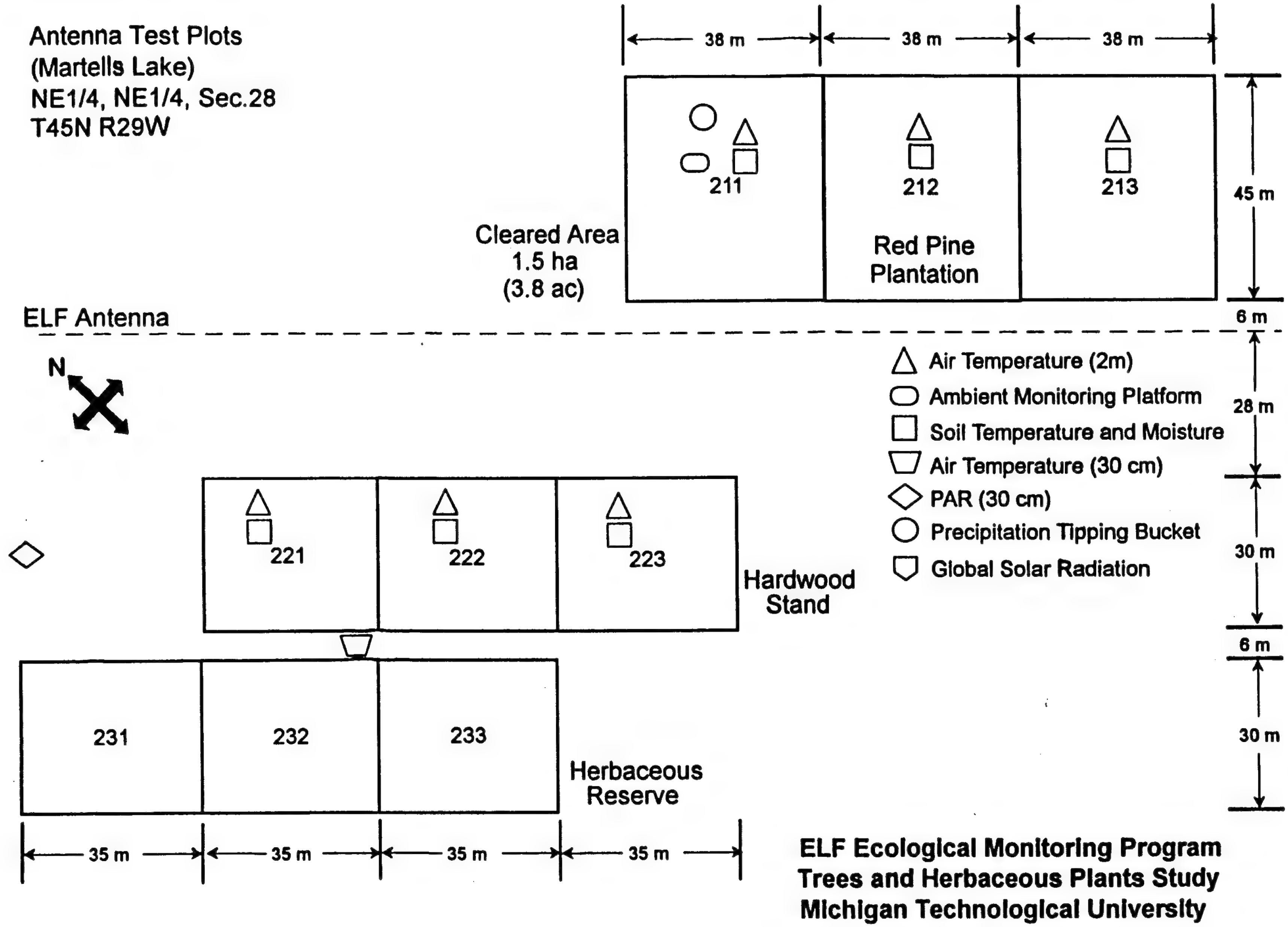
ANT = Overhead Antenna Plots
GND = Ground Terminal Plots



ELF Ecological Monitoring Program
Trees and Herbaceous Plants Study
Michigan Technological University



Ground Terminal Plantation Plots
(Martells Lake)
NW 1/4, NE1/4, Sec. 28
T45N - R29W
N
Overhead ground Feed Wire
Approx. location of buried Ground
Cleared Area
1.8 ha
(4.4 ac)
PINE PLANTATION
112
111
113
51 m
26 m
49 m
49 m
4.2 m
Air Temperature (2m)
Ambient Monitoring Platform
Soil Temperature and Moisture
Air Temperature (30 cm)
PAR (30 cm)
Precipitation Tipping Bucket
Global Solar Radiation
ELF Ecological Monitoring Program
Trees and Herbaceous Plants Study
Michigan Technological University

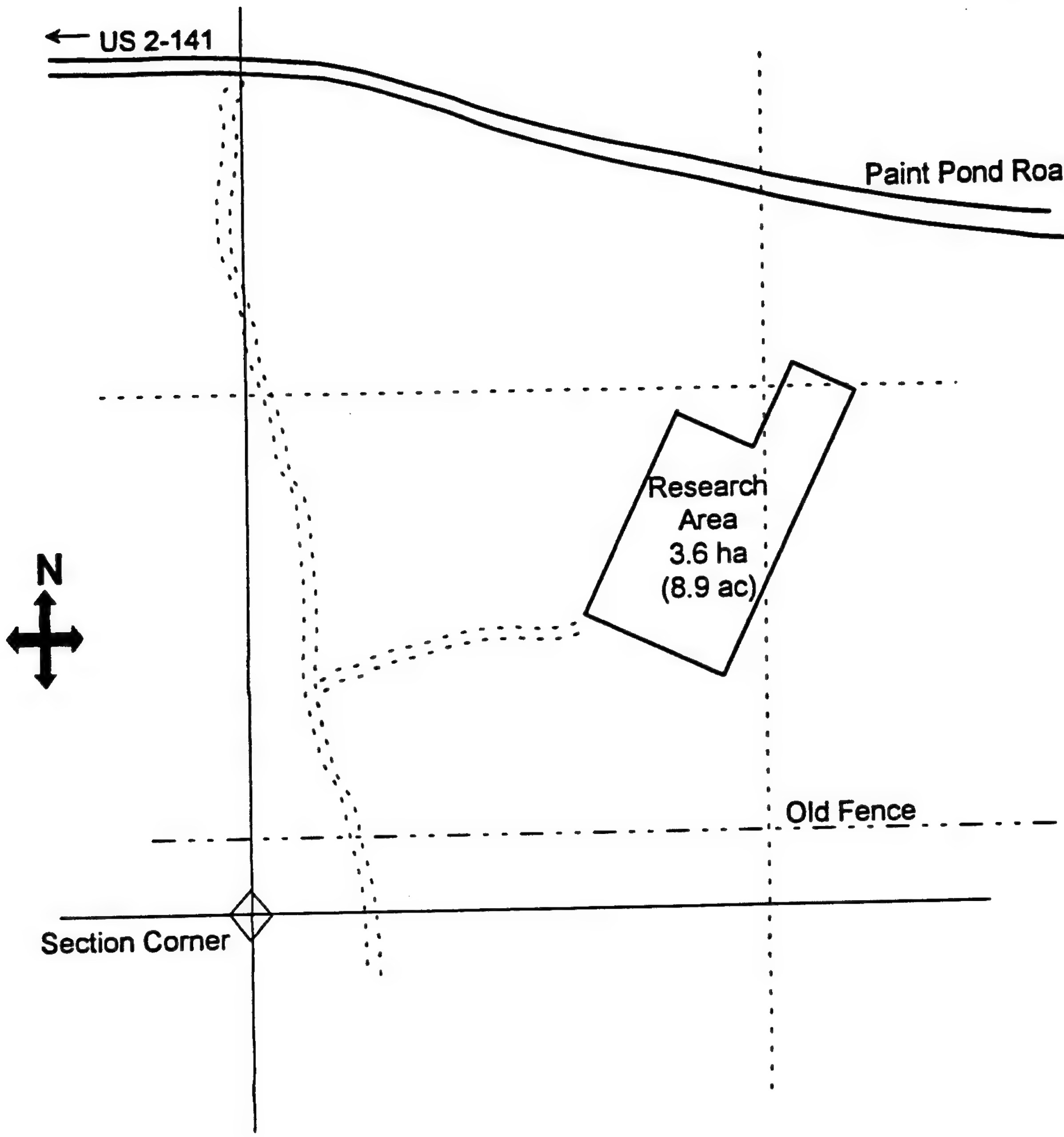


Antenna Test Plots
(Martells Lake)
NE1/4, NE1/4, Sec.28
T45N R29W
38 m
38 m
38 m
211
212
213
45 m
Cleared Area
1.5 ha
(3.8 ac)
Red Pine
Plantation
ELF Antenna
6 m
N
Air Temperature (2m)
Ambient Monitoring Platform
Soil Temperature and Moisture
Air Temperature (30 cm)
PAR (30 cm)
Precipitation Tipping Bucket
Global Solar Radiation
28 m
30 m
6 m
30 m
221
222
223
Hardwood
Stand
231
232
233
Herbaceous
Reserve
35 m
35 m
35 m
35 m
ELF Ecological Monitoring Program
Trees and Herbaceous Plants Study
Michigan Technological University

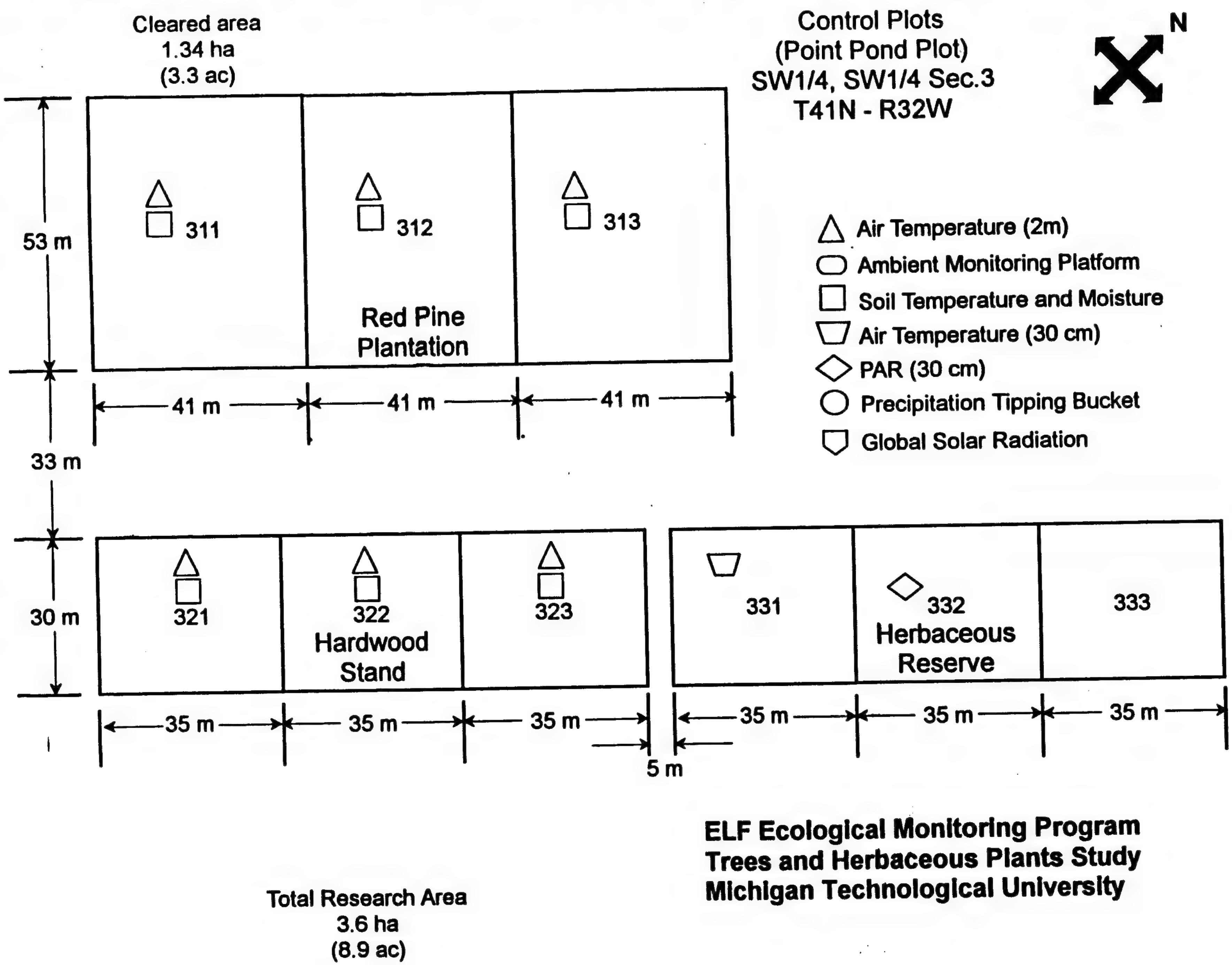
ELF CONTROL PLOTS

(Paint Pond Road)

SW 1/4, SW 1/4. Sec. 3
T41N - R32W



ELF Ecological Monitoring System
Trees and Herbaceous Plants Study
Michigan Technological University



Cleared area
1.34 ha
(3.3 ac)
Control Plots
(Point Pond Plot)
SW1/4, SW1/4 Sec.3
T41N - R32W
N
311
312
313
Red Pine
Plantation
53 m
41 m
41 m
41 m
33 m
Air Temperature (2m)
Ambient Monitoring Platform
Soil Temperature and Moisture
Air Temperature (30 cm)
PAR (30 cm)
Precipitation Tipping Bucket
Global Solar Radiation
321
322
Hardwood
Stand
323
331
332
Herbaceous
Reserve
333
30 m
35 m
35 m
35 m
35 m
35 m
35 m
5 m
Total Research Area
3.6 ha
(8.9 ac)
ELF Ecological Monitoring Program
Trees and Herbaceous Plants Study
Michigan Technological University

APPENDIX C

Soil Profile Descriptions

Soil Classification
Ground Site

Pedon Classification: Alfic Haplorthod; sandy, mixed, frigid.
Location: Marquette County, Michigan
Vegetation and Land Use: Northern hardwoods. Forested.
Parent Material: Outwash.
Physiographic Position: Rolling. Upland.
Topography: Undulating.
Drainage: Well drained.
Groundwater: Below 175 cm.
Sampled by: C. Trettin, P. Cattelino.

(All colors are for moist condition unless otherwise stated.)

0a 3 to 0 cm (1 to 0 inches). Well decomposed hardwood litter.

A 407 0 to 5 cm (0 to 2 inches). Dark reddish brown (5YR 2.5/2) loamy sand; weak fine granular structure; friable; many fine and medium, and few coarse roots; 3 percent coarse fragments; abrupt wavy boundary. (2 to 6 cm thick)

E 408 5 to 14 cm (2 to 6 inches). Pinkish gray (5YR 6/2) sand; weak fine granular structure; very friable; many fine and medium, and common coarse roots; 3 percent coarse fragments; abrupt wavy boundary. (6 to 23 cm thick)

Bsl 409 14 to 45 cm (6 to 18 inches). Yellowish red (5YR 5/6) sand; weak fine subangular blocky structure; friable; common fine and medium roots; 2 percent coarse fragments; clear wavy boundary. (19 to 38 cm thick)

Bs2 410 45 to 72 cm (18 to 28 inches). Yellowish red (5YR 5/8) sand; weak fine subangular blocky structure; very friable; common fine and few medium roots; 15 percent coarse fragments with a stone line comprised of rounded cobbles; clear wavy boundary. (18 to 24 cm thick)

2Bt 411 72 to 92 cm (28 to 36 inches). Strong brown (7.5YR 4/6) fine sandy loam with few thin reddish brown (5YR 4/4) clay films; medium subangular blocky structure; friable; few fine and medium roots; 50 percent coarse fragments; clear wavy boundary. (9 to 21 cm thick)

2C 412 92 to 175 cm (36 to 69 inches). Dark reddish brown (5YR 3/4) sandy loam; weak fine granular structure; friable; few fine and medium roots; 70 percent coarse fragments.

Soil Classification
Antenna Site

Pedon Classification: Entic Haplorthod; sandy, mixed, frigid.
Location: Marquette County, Michigan
Vegetation and Land Use: Northern hardwoods. Forested.
Parent Material: Outwash over water-worked till.
Physiographic Position: Rolling upland.
Topography: Undulating. Gradient is 7 percent. South aspect. Concave. Slope length is 200 ft.
Drainage: Well drained.
Groundwater: Below 160 cm.
Sampled by: C. Trettin, C. Becker, E. Padley, K. Warren.

(All colors are for moist condition unless otherwise stated.)

0i 2 to 1 cm (1 to .2 inches). Undecomposed hardwood litter.

0a 1 to 0 cm (.2 to 0 inches). Well decomposed hardwood litter; many fine and common medium roots.

A 388 0 to 2 cm (0 to 1 inch). Black (N2/) loamy sand; weak fine granular structure; very friable; many fine and medium, and few coarse roots; very strongly acid; abrupt smooth boundary. (2 to 3 cm thick)

E 389 2 to 13 cm (1 to 5 inches). Pinkish gray (7.5YR 6/2) sand; weak fine granular structure; very friable; many fine and medium, and common coarse roots; 2 percent coarse fragments; strongly acid; abrupt wavy boundary. (5 to 13 cm thick)

Bsl 390 13 to 27 cm (5 to 11 inches). Dark brown (7.5YR 4/4) loamy sand; weak fine subangular blocky structure; friable; many fine and medium, and common coarse roots; 3 percent coarse fragments; strongly acid; abrupt wavy boundary. (12 to 16 cm thick)

Bs2 391 27 to 43 cm (11 to 17 inches). Yellowish red (5YR 4/6) fine sand; weak fine subangular blocky structure; friable; common fine and medium, and few coarse roots; 3 percent coarse fragments; moderately acid; clear wavy boundary. (12 to 19 cm thick)

Bs3 392 43 to 66 cm (17 to 26 inches). Strong brown (7.5YR 5/6) sand; weak fine granular structure; very friable; few fine and medium roots; 1 percent coarse fragments; moderately acid; clear irregular boundary. (22 to 65 cm thick)

2BC 393 66 to 90 cm (26 to 35 inches). Dark brown (7.5YR 4/4) very stony loamy sand; moderate medium subangular blocky structure; friable; few fine and medium roots; 30 percent coarse fragments in stone line at top of till; moderately acid; gradual wavy boundary. (23 to 28 cm thick)

2C 394 90 to 160 cm (35 to 63 inches). Strong brown (7.5YR 4/6) very stony loamy sand; weak fine granular structure; friable; few fine and medium roots; 30 percent coarse fragments; moderately acid.

Soil Classification
Control Site

Pedon Classification: Alfic Haplorthod; coarse-loamy, mixed, frigid.
Location: Iron County, Michigan. SW¼, SW¼ Section 3, T41N, R32W.
Climate: Average annual precipitation is about 850 mm; mean annual air temperature is about 8°C.
Vegetation and Land Use: Woodland (Red oak, white birch, aspen, sugar maple).
Parent Material: Glacial till.
Physiographic Position: Rolling upland.
Topography: Complex slopes. Gradient is 3 to 5 percent. Southeast aspect. Concave, upper slope position. Slope length is 30 meters.
Groundwater: Below 230 cms.
Sampled by: R. Wendell, B. Wilczynski. September 20, 1984.

(All colors are for moist conditions.)

0i 548 5 to 2 cm. Undecomposed hardwood leaves and twigs; very strongly acid; abrupt smooth boundary. (2 to 3 cm thick)

0e 549 2 to 0 cm. Partially decomposed hardwood litter; very strongly acid; abrupt smooth boundary. (0 to 2 cm thick)

A 550 0 to 4 cm. Dark reddish brown (5YR 2.5/2) fine sandy loam; weak fine granular structure; very friable; many fine roots; extremely acid; clear smooth boundary. (2 to 5 cm thick)

E 551 4 to 9 cm. Pinkish gray (5YR 6/2) fine loamy sand; weak fine subangular blocky structure; friable many fine and common medium roots; extremely acid; clear wavy boundary. (5 to 9 cm thick)

Bs1 552 9 to 32 cm. Yellowish red (5YR 4/6) fine loamy sand; moderate medium subangular blocky structure; friable; many fine, common medium and few coarse roots; 3 percent pebbles; medium acid; gradual smooth boundary. (19 to 23 cm thick)

Bs2 553 32 to 55 cm. Yellowish red (5YR 5/8) fine sand; strong medium subangular blocky structure; friable; few fine and many medium roots; 4 percent pebbles; slightly acid; clear smooth boundary. (20 to 23 cm thick)

E' 554 55 to 67 cm. Reddish brown (5YR 5/3) fine sandy loam; moderate medium subangular blocky structure; friable few medium roots; few fine vesicular pores; 9 percent pebbles; medium acid; gradual smooth boundary. (12 to 14 cm thick)

(B/E)1 555 67 to 105 cm. Reddish brown (5YR 4/4) gravelly fine sandy loam (Bt) and light reddish brown (5YR 6/4) fine loamy sand (E); strong fine subangular blocky structure (Bt) and strong medium subangular blocky structure (E); friable; few fine and few medium roots; few fine vesicular pores; 34 percent pebbles; medium acid; gradual smooth boundary. (38 to 40 cm thick)

(B/E)2 556 105 to 124 cm. Red (2.5YR 4/6) sandy loam (Bt) and yellowish red (5YR 5/6) loamy sand (E); strong medium subangular blocky structure; friable; few fine roots; few very fine vesicular pores; 13 percent pebbles; slightly acid; clear smooth boundary. (17 to 19 cm thick)

C 557 124 to 230 cm. Yellowish red (5YR 5/6) sand; single grain; loose; 8 percent pebbles; slightly acid; few irregularly spaced red (2.5YR 4/6) loamy sand bands.

NOTE: A layer with 70 percent pebble content occurred between 89 and 109 cm.

APPENDIX D

ELF Electromagnetic Field Exposure Data

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616-3799
since 1936

312/567-4000

21 January 1994

Glen Mroz, Ph.D.
Department of Forestry
Michigan Technological University
Houghton, MI 49931

RE: 1993 ELF EM Exposure Information

Dear Dr. Mroz:

In support of your final data analyses, the following are enclosed:

- 1993 EM exposure values
- Paired-site EM exposure ratios based on 1993 values
- Fixed probe earth electric field values
- NRTF-Republic operating parameters for January-October 1993.

The EM field measurement report will be distributed in March. Please contact me if you have any questions regarding this material or need additional information prior to your receipt of this report.

Sincerely,

IIT RESEARCH INSTITUTE

David P. Haradem

David P. Haradem
Senior Engineer
(312) 567-4622

Enclosures (4)

DPH/bjm

cc: JPickens
JEZapotosky
File

TABLE D-3. 60 Hz AIR ELECTRIC FIELD INTENSITIES (V/m)
Upland Flora and Soil Microflora Studies
(page 1 of 2)

Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4C1-6	-	0.003	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-7	-	0.006	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-8	-	0.004	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-9	-	0.002	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-10	-	-	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-11	-	-	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-12	-	-	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4C1-13	-	-	<	<	<	<	<[d]	<[b]	<[d]	/	<[d]
4T2-3	-	0.001	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-4	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-5	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-6	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-7	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-8	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-9	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T2-10	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T2-11	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T2-12	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-13	-	-	<	<	<	/	#[d]	#[d]	/	<[b]	<[b]
4T2-14	-	-	<	<	<	/	#[d]	#[d]	/	/	<[b]
4T2-15	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T2-16	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T2-17	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T2-18	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T2-19	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T2-26	-	-	-	-	-	-	-	#[d]	/	<[b]	<[b]
4T2-33	-	-	-	-	-	-	-	#[d]	/	<[b]	<[b]
4T2-34	-	-	-	-	-	-	-	#[d]	/	<[b]	<[b]
4T2-35	-	-	-	-	-	-	-	#[d]	/	<[b]	<[b]
4T2-36	-	-	-	-	-	-	-	#[d]	/	<[b]	<[b]

TABLE D-3. 60 Hz AIR ELECTRIC FIELD INTENSITIES (V/m)
Upland Flora and Soil Microflora Studies
(page 2 of 2)

Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4T4-4	-	0.003	<	<	<0.001	/	#[d]	#[d]	/	<[b]	<[b]
4T4-5	-	-	<	<	0.006	/	#[d]	#[d]	/	<[b]	<[b]
4T4-6	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T4-7	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T4-8	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T4-9	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T4-10	-	-	<	<	<	<	#[d]	#[d]	/	<[b]	<[b]
4T4-11	-	-	<	<	0.010	/	#[d]	#[d]	/	<[b]	<[b]
4T4-12	-	-	-	<	0.005	/	#[d]	#[d]	/	<[b]	<[b]
4T4-13	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-14	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-15	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-16	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-17	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-18	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-19	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4T4-20	-	-	-	-	-	-	#[d]	#[d]	/	<[b]	<[b]
4S1-1	-	-	-	-	0.013	0.033	0.011[b]	0.017[b]	0.018[b]	0.007[b]	/
4S2-1	-	-	-	-	<	<	<[d]	<[b]	<[d]	<[d]	/
4S3-1	-	-	-	-	<0.001	<0.001	<0.001[b]	<0.001[b]	/	<[b]	/

a = antennas not constructed.
b = antennas off, grounded at transmitter.
c = antennas off, connected to transmitter.
d = antennas on, 150 ampere current.

\- = measurement point not established.
/ = measurement not taken.
\# = measurement precluded by antenna operation.
< = measurement estimated <0.001 V/m based on earth electric field.

TABLE D-4. 60 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Studies
(page 1 of 2)

Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4C1-6	-	0.022	0.016	0.005	0.043	0.023	0.016[d]	0.024[b]	0.012[d]	1.51[d]	0.022[d]
4C1-7	-	0.143	0.123	0.077	0.178	0.118	0.030[d]	0.039[b]	0.043[d]	6.7[d]	0.064[d]
4C1-8	-	0.104	0.117	0.077	0.131	0.078	0.018[d]	0.063[b]	0.020[d]	6.1[d]	0.049[d]
4C1-9	-	0.011	0.019	0.024	0.034	0.032	0.023[d]	0.023[b]	0.018[d]	1.64[d]	0.022[d]
4C1-10	-	-	0.090	0.068	0.118	0.106	0.054[d]	0.041[b]	0.030[d]	7.5[d]	0.059[d]
4C1-11	-	-	0.160	0.107	0.132	0.146	0.066[d]	0.068[b]	0.048[d]	9.1[d]	0.077[d]
4C1-12	-	-	0.104	0.101	0.075	0.093	0.042[d]	0.042[b]	0.033[d]	4.2[d]	0.055[d]
4C1-13	-	-	0.040	0.030	0.046	0.065	0.025[d]	0.039[b]	0.014[d]	2.9[d]	0.026[d]
4T2-3	-	0.51	0.39	0.194	0.27	0.28	#[d]	#[d]	0.52[b]	0.20[b]	0.25[b]
4T2-4	-	-	0.27	0.24	0.30	0.25	#[d]	#[d]	0.59[b]	0.24[b]	0.199[b]
4T2-5	-	-	0.43	0.32	0.20	0.20	#[d]	#[d]	0.77[b]	0.25[b]	0.24[b]
4T2-6	-	-	0.66	0.46	0.192	0.22	#[d]	#[d]	0.84[b]	0.30[b]	0.31[b]
4T2-7	-	-	0.42	0.52	0.197	0.28	#[d]	#[d]	0.71[b]	0.22[b]	0.32[b]
4T2-8	-	-	0.47	0.190	0.22	/	#[d]	#[d]	0.79[b]	0.24[b]	0.28[b]
4T2-9	-	-	0.49	0.31	0.183	0.25	#[d]	#[d]	0.62[b]	0.23[b]	0.26[b]
4T2-10	-	-	0.44	0.32	0.155	0.166	#[d]	#[d]	0.71[b]	0.25[b]	0.33[b]
4T2-11	-	-	0.51	0.40	0.31	0.43	#[d]	#[d]	0.72[b]	0.34[b]	0.33[b]
4T2-12	-	-	0.47	0.38	0.24	/	#[d]	#[d]	0.73[b]	0.28[b]	0.35[b]
4T2-13	-	-	0.76	0.31	0.31	0.25	#[d]	#[d]	0.87[b]	0.27[b]	0.28[b]
4T2-14	-	-	0.61	0.29	0.35	0.21	#[d]	#[d]	0.78[b]	0.28[b]	0.29[b]
4T2-15	-	-	-	-	-	-	#[d]	#[d]	1.01[b]	0.35[b]	0.59[b]
4T2-16	-	-	-	-	-	-	#[d]	#[d]	0.66[b]	0.23[b]	0.30[b]
4T2-17	-	-	-	-	-	-	#[d]	#[d]	0.93[b]	0.173[b]	0.31[b]
4T2-18	-	-	-	-	-	-	#[d]	#[d]	0.73[b]	0.158[b]	0.29[b]
4T2-19	-	-	-	-	-	-	#[d]	#[d]	0.64[b]	0.25[b]	0.36[b]
4T2-26	-	-	-	-	-	-	-	#[d]	0.61[b]	0.26[b]	0.30[b]
4T2-33	-	-	-	-	-	-	-	#[d]	0.75[b]	0.27[b]	0.34[b]
4T2-34	-	-	-	-	-	-	-	#[d]	0.81[b]	0.28[b]	0.35[b]
4T2-35	-	-	-	-	-	-	-	#[d]	0.73[b]	0.26[b]	0.35[b]
4T2-36	-	-	-	-	-	-	-	#[d]	0.60[b]	0.30[b]	0.32[b]

TABLE D-4. 60 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Studies
(page 2 of 2)

Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4T4-4	-	0.72	0.42	0.185	0.56	0.079	#[d]	#[d]	0.40[b]	0.30[b]	0.32[b]
4T4-5	-	-	0.58	0.58	4.3	1.12	#[d]	#[d]	3.1[b]	3.2[b]	2.6[b]
4T4-6	-	-	0.22	0.16	0.61	0.188	#[d]	#[d]	0.35[b]	0.45[b]	0.37[b]
4T4-7	-	-	0.44	0.29	0.64	0.22	#[d]	#[d]	0.28[b]	0.32[b]	0.48[b]
4T4-8	-	-	0.42	0.193	0.40	0.23	#[d]	#[d]	0.27[b]	0.28[b]	0.30[b]
4T4-9	-	-	0.50	0.21	0.27	0.073	#[d]	#[d]	0.31[b]	0.36[b]	0.24[b]
4T4-10	-	-	0.42	0.22	0.29	0.063	#[d]	#[d]	0.23[b]	0.28[b]	0.30[b]
4T4-11	-	-	0.40	0.60	2.7	1.27	#[d]	#[d]	4.1[b]	3.8[b]	3.3[b]
4T4-12	-	-	-	0.75	3.4	1.35	#[d]	#[d]	0.34[b]	2.2[b]	1.78[b]
4T4-13	-	-	-	-	-	-	#[d]	#[d]	0.22[b]	0.26[b]	0.30[b]
4T4-14	-	-	-	-	-	-	#[d]	#[d]	0.53[b]	0.78[b]	0.38[b]
4T4-15	-	-	-	-	-	-	#[d]	#[d]	1.29[b]	1.86[b]	0.99[b]
4T4-16	-	-	-	-	-	-	#[d]	#[d]	4.4[b]	4.8[b]	4.4[b]
4T4-17	-	-	-	-	-	-	#[d]	#[d]	/	2.1[b]	/
4T4-18	-	-	-	-	-	-	#[d]	#[d]	4.6[b]	4.7[b]	4.7[b]
4T4-19	-	-	-	-	-	-	#[d]	#[d]	1.17[b]	1.02[b]	0.75[b]
4T4-20	-	-	-	-	-	-	#[d]	#[d]	0.27[b]	0.33[b]	0.33[b]
4S1-1	-	-	-	-	8.5	12.2	11.6[b]	15.7[b]	9.1[b]	3.3[b]	/
4S2-1	-	-	-	-	0.155	0.109	0.032[b]	0.068[b]	0.060[b]	7.2[b]	/
4S3-1	-	-	-	-	0.65	1.73	0.73[b]	0.87[b]	0.69[b]	0.43[b]	/

a = antennas not constructed.
b = antennas off, grounded at transmitter.
c = antennas off, connected to transmitter.
d = antennas on, 150 ampere current.

\- = measurement point not established.
/ = measurement not taken.
= measurement precluded by antenna operation.

TABLE D-5. 60 Hz MAGNETIC FLUX DENSITIES (mG)
Upland Flora and Soil Microflora Studies
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Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4C1-6	-	0.003	0.003	0.003	0.002	0.003	0.002[d]	0.002[b]	0.001[d]	0.28[d]	0.004d
4C1-7	-	0.003	0.002	0.001	0.003	0.002	0.001[d]	0.002[b]	0.001[d]	0.25[d]	0.001d
4C1-8	-	0.003	0.003	0.002	0.003	0.002	0.001[d]	0.002[b]	0.002[d]	0.24[d]	0.002d
4C1-9	-	0.003	0.003	0.002	0.001	0.002	0.002[d]	0.002[b]	0.001[d]	0.29[d]	0.004d
4C1-10	-	-	0.002	0.002	0.002	0.002	0.002[d]	0.002[b]	0.001[d]	0.22[d]	0.002d
4C1-11	-	-	0.002	0.002	0.002	0.002	0.001[d]	0.002[b]	0.001[d]	0.23[d]	0.002d
4C1-12	-	-	0.002	0.003	0.001	0.002	0.001[d]	0.002[b]	0.001[d]	0.26[d]	0.002d
4C1-13	-	-	0.002	0.003	0.001	0.003	0.002[d]	0.002[b]	0.001[d]	0.30[d]	0.003d
4T2-3	-	0.002	0.001	0.001	0.003	0.005	#[d]	#[d]	0.004[b]	0.002[b]	0.002b
4T2-4	-	-	0.001	0.001	0.003	0.006	#[d]	#[d]	0.005[b]	0.002[b]	0.003b
4T2-5	-	-	0.001	0.007	0.017	0.030	#[d]	#[d]	0.029[b]	0.004[b]	0.011b
4T2-6	-	-	0.001	0.006	0.006	0.014	#[d]	#[d]	0.017[b]	0.001[b]	0.005b
4T2-7	-	-	0.001	0.004	0.004	0.007	#[d]	#[d]	0.010[b]	0.001[b]	0.003b
4T2-8	-	-	0.001	0.002	0.004	/	#[d]	#[d]	0.010[b]	0.001[b]	0.002b
4T2-9	-	-	0.001	0.003	0.003	0.005	#[d]	#[d]	0.007[b]	0.001[b]	0.002b
4T2-10	-	-	0.001	0.003	0.003	0.005	#[d]	#[d]	0.007[b]	0.001[b]	0.002b
4T2-11	-	-	0.001	0.004	0.005	0.007	#[d]	#[d]	0.009[b]	0.002[b]	0.003b
4T2-12	-	-	0.002	0.004	0.005	/	#[d]	#[d]	0.010[b]	0.002[b]	0.003b
4T2-13	-	-	0.001	0.005	0.008	0.013	#[d]	#[d]	0.016[b]	0.002[b]	0.004b
4T2-14	-	-	0.002	0.011	0.018	0.029	#[d]	#[d]	0.035[b]	0.004[b]	0.011b
4T2-15	-	-	-	-	-	-	#[d]	#[d]	0.043[b]	0.005[b]	0.013b
4T2-16	-	-	-	-	-	-	#[d]	#[d]	0.033[b]	0.004[b]	0.011b
4T2-17	-	-	-	-	-	-	#[d]	#[d]	0.016[b]	0.003[b]	0.005b
4T2-18	-	-	-	-	-	-	#[d]	#[d]	0.009[b]	0.002[b]	0.003b
4T2-19	-	-	-	-	-	-	#[d]	#[d]	0.004[b]	0.002[b]	0.003b
4T2-26	-	-	-	-	-	-	-	#[d]	0.015[b]	0.001[b]	0.004b
4T2-33	-	-	-	-	-	-	-	#[d]	0.008[b]	0.001[b]	0.002b
4T2-34	-	-	-	-	-	-	-	#[d]	0.012[b]	0.001[b]	0.003b
4T2-35	-	-	-	-	-	-	-	#[d]	0.030[b]	0.001[b]	0.009b
4T2-36	-	-	-	-	-	-	-	#[d]	0.042[b]	0.003[b]	0.014b

TABLE D-5. 60 Hz MAGNETIC FLUX DENSITIES (mG)
Upland Flora and Soil Microflora Studies
(page 2 of 2)

Site No., Meas. Pt.	1983[a]	1984[a]	1985[a]	1986[b]	1987[c]	1988[c]	1989	1990	1991	1992	1993
4T4-4	-	0.004	0.002	0.001	0.003	0.003	#[d]	#[d]	0.003[b]	0.002[b]	0.002b
4T4-5	-	-	0.002	0.006	0.010	0.017	#[d]	#[d]	0.008[b]	0.008[b]	0.008b
4T4-6	-	-	0.002	0.001	0.004	0.007	#[d]	#[d]	0.002[b]	0.003[b]	0.003b
4T4-7	-	-	0.001	0.001	0.004	0.005	#[d]	#[d]	0.002[b]	0.003[b]	0.002b
4T4-8	-	-	0.002	0.001	0.004	0.005	#[d]	#[d]	0.002[b]	0.003[b]	0.002b
4T4-9	-	-	0.002	0.001	0.002	0.003	#[d]	#[d]	0.001[b]	0.002[b]	0.002b
4T4-10	-	-	0.001	0.001	0.002	0.002	#[d]	#[d]	0.001[b]	0.002[b]	0.002b
4T4-11	-	-	0.002	0.002	0.002	0.019	#[d]	#[d]	0.008[b]	0.010[b]	0.011b
4T4-12	-	-	-	0.002	0.010	0.016	#[d]	#[d]	0.006[b]	0.008[b]	0.007b
4T4-13	-	-	-	-	-	-	#[d]	#[d]	0.001[b]	0.002[b]	0.003b
4T4-14	-	-	-	-	-	-	#[d]	#[d]	0.001[b]	0.003[b]	0.004b
4T4-15	-	-	-	-	-	-	#[d]	#[d]	0.003[b]	0.005[b]	0.007b
4T4-16	-	-	-	-	-	-	#[d]	#[d]	0.012[b]	0.015[b]	0.010b
4T4-17	-	-	-	-	-	-	#[d]	#[d]	0.013[b]	0.016[b]	0.009b
4T4-18	-	-	-	-	-	-	#[d]	#[d]	0.009[b]	0.011[b]	0.008b
4T4-19	-	-	-	-	-	-	#[d]	#[d]	0.003[b]	0.005[b]	0.004b
4T4-20	-	-	-	-	-	-	#[d]	#[d]	0.002[b]	0.004[b]	0.003b
4S1-1	-	-	-	-	0.035	0.043	0.052[b]	0.052[b]	0.032[b]	0.012[b]	/
4S2-1	-	-	-	-	0.003	0.002	0.002[d]	0.001[b]	0.001[d]	0.23[d]	/
4S3-1	-	-	-	-	0.036	0.095	0.028[b]	0.030[b]	0.035[b]	0.020[b]	/

a = antennas not constructed.
b = antennas off, grounded at transmitter.
c = antennas off, connected to transmitter.
d = antennas on, 150 ampere current.

\- = measurement point not established.
/ = measurement not taken.
= measurement precluded by antenna operation.

TABLE D-6. 76 Hz AIR ELECTRIC FIELD INTENSITIES (V/m)
Upland Flora and Soil Microflora Studies
(page 1 of 2)

Site No.,	1986				1987		1988		1989	1990	1991		1992	1993
	NS	NEW	SEW	SEW	NS	EW	NS	EW	B	B	NS	B	B	B
Meas. Pt.	4 A	6 A	6 A	10 A, EX	15 A	15 A	75 A	75 A	150 A	150 A	150 A	150 A	150 A	150 A
4C1-6	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-7	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-8	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-9	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-10	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-11	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-12	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4C1-13	<	<	<	*	<	<	<	<	<	<	/	/	<	<
4T2-3	<	<	0.004	0.007	0.002	0.014	/	/	0.142	0.110	0.047	0.122	/	0.100
4T2-4	<	<	0.005	0.008	0.001	0.014	/	/	0.149	0.122	0.041	0.095	/	0.092
4T2-5	0.018	<	0.092	0.153	0.003	0.23	/	/	1.31	1.16	0.30	1.08	/	1.07
4T2-6	<	<	0.005	0.008	0.003	0.013	/	/	0.138	0.148	0.051	0.123	/	0.155
4T2-7	<	<	0.007	0.012	0.001	0.018	/	/	0.173	0.177	0.044	0.150	/	0.20
4T2-8	<	<	0.004	0.007	0.002	0.012	/	/	0.124	0.112	0.045	0.103	/	0.102
4T2-9	<	<	0.005	0.008	0.002	0.010	/	/	0.116	0.119	0.031	0.110	/	0.101
4T2-10	<	<	0.004	0.007	0.002	0.011	/	/	0.113	0.076	0.034	0.112	/	0.104
4T2-11	<	<	0.003	0.005	0.002	0.012	/	/	0.22	0.180	0.042	0.132	/	0.104
4T2-12	<	<	0.002	0.003	0.002	0.014	/	/	0.095	0.096	0.041	0.086	/	0.087
4T2-13	<	<	0.005	0.008	0.002	0.012	/	/	0.125	0.130	0.036	0.125	/	0.117
4T2-14	0.030	<	0.155	0.26	0.003	0.186	/	/	1.66	1.94	0.23	1.68	/	1.14
4T2-15	-	-	-	-	-	-	-	-	2.3	1.67	0.32	0.58	/	0.70
4T2-16	-	-	-	-	-	-	-	-	1.92	1.84	0.46	1.17	/	0.35
4T2-17	-	-	-	-	-	-	-	-	0.69	0.59	0.075	0.27	/	0.149
4T2-18	-	-	-	-	-	-	-	-	0.28	0.21	0.039	0.152	/	0.157
4T2-19	-	-	-	-	-	-	-	-	0.107	0.105	0.029	0.092	/	0.100
4T2-26	-	-	-	-	-	-	-	-	-	0.182	0.059	0.136	/	0.159
4T2-33	-	-	-	-	-	-	-	-	-	0.141	0.042	0.146	/	0.144
4T2-34	-	-	-	-	-	-	-	-	-	0.144	0.041	0.129	/	0.132
4T2-35	-	-	-	-	-	-	-	-	-	0.24	0.101	0.38	/	0.38
4T2-36	-	-	-	-	-	-	-	-	-	4.7	0.94	4.7	/	4.1

TABLE D-6. 76 Hz AIR ELECTRIC FIELD INTENSITIES (V/m)
Upland Flora and Soil Microflora Studies
(page 2 of 2)

Site No., Meas. Pt.	1986				1987		1988		1989	1990	1991		1992	1993
	NS 4 A	NEW 6 A	SEW 6 A	SEW 10 A, EX	NS 15 A	EW 15 A	NS 75 A	EW 75 A	B 150 A	B 150 A	NS 150 A	B 150 A	B 150 A	B 150 A
4T4-4	<	<	0.006	0.010	0.002	0.005	/	/	0.067	0.058	0.015	0.071	/	0.043
4T4-5	0.033	0.008	0.20	0.33	0.019	0.27	/	/	4.8	3.8	1.37	4.4	/	14.1
4T4-6	0.005	<	0.023	0.038	0.002	0.021	/	/	0.175	0.117	0.040	0.186	/	0.144
4T4-7	<	<	0.006	0.010	0.002	0.015	/	/	0.133	0.129	0.026	0.33	/	0.124
4T4-8	<	<	0.008	0.013	0.002	0.016	/	/	0.145	0.145	0.032	0.130	/	0.118
4T4-9	<	<	0.009	0.015	0.001	0.008	/	/	0.095	0.072	0.017	0.130	/	0.080
4T4-10	<	<	0.007	0.012	0.001	0.001	/	/	0.112	0.085	0.026	0.107	/	0.065
4T4-11	<	0.005	0.38	0.63	0.025	0.43	/	/	5.0	4.6	1.37	4.8	/	3.2
4T4-12	0.055	0.005	0.43	0.72	0.017	0.30	/	/	4.5	3.8	1.26	4.6	/	5.1
4T4-13	-	-	-	-	-	-	-	-	0.26	0.21	0.042	0.28	/	0.121
4T4-14	-	-	-	-	-	-	-	-	0.88	0.84	0.194	0.90	/	0.51
4T4-15	-	-	-	-	-	-	-	-	2.7	2.6	0.51	2.8	/	1.77
4T4-16	-	-	-	-	-	-	-	-	5.9	5.4	1.68	6.7	/	3.7
4T4-17	-	-	-	-	-	-	-	-	4.5	4.3	1.28	5.7	/	3.5
4T4-18	-	-	-	-	-	-	-	-	4.8	3.8	1.24	4.9	/	4.2
4T4-19	-	-	-	-	-	-	-	-	1.16	0.96	0.25	1.15	/	0.54
4T4-20	-	-	-	-	-	-	-	-	0.32	0.183	0.067	0.47	/	0.166
4S1-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/
4S2-1	-	-	-	-	<	<	<	<	<	<	<	<	<	/
4S3-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/

NS = north-south antenna.
EW = east-west antenna.
NEW = northern EW antenna element.
SEW = southern EW antenna element.
B = NS + EW antennas, standard phasing.
EX = extrapolated data.

\- = measurement point not established.
/ = measurement not taken.
< = measurement estimated <0.001 V/m based on earth electric field.
* = data cannot be extrapolated.

TABLE D-7. 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Studies
(page 1 of 2)

Site No., Meas. Pt.	1986 NS 4 A	1986 NEW 6 A	1986 SEW 6 A	1986 SEW 10 A, EX	1987 NS 15 A	1987 EW 15 A	1988 NS 75 A	1988 EW 75 A	1989 B 150 A	1990 B 150 A	1991 NS 150 A	1991 B 150 A	1992 B 150 A	1993 B 150 A
4C1-6	<0.001	<0.001	<0.001	*	0.002	0.002	0.007	0.005	0.030	0.028	/	0.026	0.029	0.030
4C1-7	<0.001	<0.001	<0.001	*	0.005	0.006	0.024	0.023	0.091	0.085	/	0.079	0.096	0.096
4C1-8	<0.001	<0.001	<0.001	*	0.004	0.004	0.017	0.016	0.076	0.067	/	0.069	0.085	0.083
4C1-9	<0.001	<0.001	<0.001	*	0.002	0.002	0.007	0.006	0.030	0.022	/	0.028	0.021	0.029
4C1-10	<0.001	<0.001	<0.001	*	0.005	0.004	0.026	0.023	0.087	0.079	/	0.089	0.095	0.094
4C1-11	<0.001	<0.001	<0.001	*	0.006	0.005	0.028	0.028	0.113	0.103	/	0.101	0.108	0.104
4C1-12	<0.001	<0.001	<0.001	*	0.004	0.003	0.016	0.016	0.068	0.072	/	0.053	0.063	0.062
4C1-13	<0.001	<0.001	<0.001	*	0.002	0.002	0.012	0.011	0.051	0.044	/	0.037	0.047	0.045
4T2-3	1.31	0.22	6.3	10.5	1.36	15.2	7.7	76	131	140	22	126	142	127
4T2-4	1.05	0.22	5.0	8.3	1.70	10.7	6.2	68	135	129	44	134	151	113
4T2-5	1.18	0.24	5.3	8.8	1.46	12.7	8.2	62	86	105	41	123	142	130
4T2-6	1.11	0.27	4.4	7.3	2.2	12.4	10.4	56	105	101	39	114	112	98
4T2-7	1.13	0.23	5.3	8.8	1.31	9.7	8.8	71	90	89	28	94	89	71
4T2-8	1.32	0.25	5.7	9.5	1.81	15.8	/	/	141	135	40	139	133	107
4T2-9	1.17	0.21	5.1	8.5	1.46	13.7	7.1	63	119	125	40	121	133	114
4T2-10	0.97	0.22	4.1	6.8	1.84	10.5	8.1	50	96	91	35	98	101	87
4T2-11	1.14	0.21	5.0	8.3	2.2	10.7	9.6	122	182	170	38	155	178	88
4T2-12	1.06	0.21	4.3	7.2	1.93	13.5	/	/	99	114	45	119	113	117
4T2-13	1.12	0.64	5.4	9.0	1.74	14.9	8.2	71	138	144	36	142	145	151
4T2-14	1.07	0.175	5.1	8.5	1.66	14.3	6.6	56	124	121	42	138	133	122
4T2-15	-	-	-	-	-	-	-	-	73	82	32	82	87	72
4T2-16	-	-	-	-	-	-	-	-	88	86	33	92	103	71
4T2-17	-	-	-	-	-	-	-	-	104	105	29	107	106	91
4T2-18	-	-	-	-	-	-	-	-	95	99	29	124	108	91
4T2-19	-	-	-	-	-	-	-	-	107	107	31	103	111	85
4T2-26	-	-	-	-	-	-	-	-	-	210	57	189	220	163
4T2-33	-	-	-	-	-	-	-	-	-	113	41	130	126	128
4T2-34	-	-	-	-	-	-	-	-	-	152	36	127	140	100
4T2-35	-	-	-	-	-	-	-	-	-	136	45	137	169	142
4T2-36	-	-	-	-	-	-	-	-	-	155	44	133	125	120

TABLE D-7. 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m) Upland Flora and Soil Microflora Studies (page 2 of 2)

Site No., Meas. Pt.	1986 NS 4 A	1986 NEW 6 A	1986 SEW 6 A	1986 SEW 10 A, EX	1987 NS 15 A	1987 EW 15 A	1988 NS 75 A	1988 EW 75 A	1989 B 150 A	1990 B 150 A	1991 NS 150 A	1991 B 150 A	1992 B 150 A	1993 B 150 A
4T4-4	0.33	0.181	1.46	2.4	1.63	3.7	7.2	16.5	42	31	10.2	25	28	45
4T4-5	13.8	2.0	81	135	14.0	194	68	910	2100	1670	510	1790	1740	1450
4T4-6	1.22	0.22	6.2	10.3	2.2	12.9	10.3	62	140	117	29	141	152	132
4T4-7	0.94	0.175	5.5	9.2	2.0	14.1	9.1	62	119	135	30	101	153	161
4T4-8	0.91	0.188	5.3	8.8	1.36	10.7	6.8	65	106	113	31	111	113	108
4T4-9	0.29	0.130	1.32	2.2	1.08	3.0	7.5	18.1	47	42	4.5	18	21	39
4T4-10	0.29	0.169	1.63	2.7	1.35	3.9	5.1	16.0	39	43	8.1	30	29	38
4T4-11	0.59	1.82	89	148	10.7	178	50	850	1870	1890	630	2200	2100	1730
4T4-12	21	2.2	118	197	13.8	260	40	760	1950	1600	380	1380	1550	1070
4T4-13	-	-	-	-	-	-	-	-	64	56	15.2	59	66	52
4T4-14	-	-	-	-	-	-	-	-	220	200	59	320	290	210
4T4-15	-	-	-	-	-	-	-	-	760	760	220	820	880	720
4T4-16	-	-	-	-	-	-	-	-	3000	3800	690	3300	3000	2700
4T4-17	-	-	-	-	-	-	-	-	130	30	/	/	/	/
4T4-18	-	-	-	-	-	-	-	-	3200	3600	1000	4100	3400	2800
4T4-19	-	-	-	-	-	-	-	-	750	880	196	880	930	430
4T4-20	-	-	-	-	-	-	-	-	200	163	49	200	210	152
4S1-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/
4S2-1	-	-	-	-	0.005	0.005	0.026	0.026	0.126	0.103	/	0.097	0.096	/
4S3-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/

NS = north-south antenna.
EW = east-west antenna.
NEW = northern EW antenna element.
SEW = southern EW antenna element.
B = NS + EW antennas, standard phasing.
EX = extrapolated data.

\- = measurement point not established.
/ = measurement not taken.
* = data cannot be extrapolated.

TABLE D-8. 76 Hz MAGNETIC FLUX DENSITIES (mG)
Upland Flora and Soil Microflora Studies
(page 1 of 2)

Site No.,	1986				1987		1988		1989	1990	1991		1992	1993
Meas. Pt.	NS 4 A	NEW 6 A	SEW 6 A	SEW 10 A, EX	NS 15 A	EW 15 A	NS 75 A	EW 75 A	B 150 A	B 150 A	NS 150 A	B 150 A	B 150 A	B 150 A
4C1-6	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	0.001	0.003	0.003	/	0.003	0.003	0.003
4C1-7	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	<0.001	0.002	0.002	/	0.002	0.002	0.002
4C1-8	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	<0.001	0.002	0.002	/	0.002	0.002	0.002
4C1-9	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	0.001	0.003	0.003	/	0.003	0.003	0.003
4C1-10	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	<0.001	0.002	0.002	/	0.002	0.002	0.002
4C1-11	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	<0.001	0.002	0.002	/	0.002	0.002	0.002
4C1-12	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	<0.001	0.002	0.002	/	0.002	0.002	0.002
4C1-13	<0.001	<0.001	<0.001	*	<0.001	<0.001	0.001	0.001	0.003	0.003	/	0.003	0.003	0.003
4T2-3	0.047	0.001	0.22	0.37	0.008	0.55	0.040	2.8	5.7	5.9	1.69	5.5	5.7	5.6
4T2-4	0.049	0.001	0.24	0.40	0.008	0.57	0.041	2.9	5.8	5.9	1.74	5.7	6.0	5.6
4T2-5	0.197	<0.001	1.00	1.67	0.011	2.4	0.061	12.4	24	27	6.9	23	26	26
4T2-6	0.058	0.001	0.44	0.73	0.006	1.16	0.020	5.0	10.3	11	3.0	10.3	10.3	10.3
4T2-7	0.046	0.001	0.22	0.37	0.006	0.59	0.024	2.6	5.4	5.8	1.63	5.4	5.4	5.5
4T2-8	0.045	0.001	0.22	0.37	0.006	0.59	/	/	5.6	5.8	1.67	5.3	5.5	5.4
4T2-9	0.029	0.001	0.138	0.23	0.007	0.38	0.027	1.72	3.4	3.6	0.96	3.3	3.5	3.3
4T2-10	0.033	0.001	0.149	0.25	0.006	0.39	0.027	1.78	3.5	3.7	1.14	3.4	3.6	3.5
4T2-11	0.043	0.001	0.21	0.35	0.006	0.56	0.025	2.6	5.0	5.3	1.54	4.9	5.1	5.0
4T2-12	0.047	0.001	0.23	0.38	0.006	0.61	/	/	5.6	5.9	1.71	5.7	5.7	5.5
4T2-13	0.086	<0.001	0.43	0.72	0.005	1.14	0.020	5.1	10.1	10.8	3.1	10.4	10.5	10.2
4T2-14	0.21	<0.001	1.03	1.72	0.012	2.5	0.061	11.9	25	28	7.7	26	27	25
4T2-15	-	-	-	-	-	-	-	-	33	36	9.6	32	33	33
4T2-16	-	-	-	-	-	-	-	-	28	29	7.8	26	27	28
4T2-17	-	-	-	-	-	-	-	-	13.6	13.9	3.9	13.0	13.2	12.9
4T2-18	-	-	-	-	-	-	-	-	8.6	8.6	2.4	7.7	8.1	7.9
4T2-19	-	-	-	-	-	-	-	-	5.9	6.0	1.73	5.7	5.9	5.9
4T2-26	-	-	-	-	-	-	-	-	-	10.5	2.8	9.7	9.9	9.4
4T2-33	-	-	-	-	-	-	-	-	-	4.2	1.21	3.8	4.0	3.8
4T2-34	-	-	-	-	-	-	-	-	-	7.4	2.1	7.0	7.0	6.7
4T2-35	-	-	-	-	-	-	-	-	-	21	5.9	20	19.1	19.3
4T2-36	-	-	-	-	-	-	-	-	-	36	10.0	33	34	35

TABLE D-8. 76 Hz MAGNETIC FLUX DENSITIES (mG)
Upland Flora and Soil Microflora Studies
(page 2 of 2)

Site No., Meas. Pt.	1986				1987		1988		1989	1990	1991		1992	1993
	NS 4 A	NEW 6 A	SEW 6 A	SEW 10 A, EX	NS 15 A	EW 15 A	NS 75 A	EW 75 A	B 150 A	B 150 A	NS 150 A	B 150 A	B 150 A	B 150 A
4T4-4	0.019	<0.001	0.096	0.160	0.005	0.24	0.027	1.15	2.5	2.3	0.63	2.3	2.4	2.6
4T4-5	0.114	0.001	0.57	0.95	0.008	1.40	0.033	6.9	13.9	13.3	4.2	13.7	14.2	16.3
4T4-6	0.045	0.001	0.22	0.37	0.008	0.53	0.034	2.7	5.3	5.1	1.60	5.3	5.6	5.9
4T4-7	0.038	0.001	0.186	0.31	0.008	0.45	0.033	2.3	4.4	4.1	1.30	4.4	4.6	4.6
4T4-8	0.035	0.001	0.179	0.30	0.007	0.43	0.033	2.1	4.2	4.1	1.25	4.2	4.4	4.7
4T4-9	0.025	0.001	0.118	0.197	0.005	0.29	0.027	1.41	2.8	2.7	0.79	2.8	3.0	3.2
4T4-10	0.022	<0.001	0.116	0.193	0.005	0.27	0.027	1.33	2.7	2.6	0.75	2.8	2.8	3.2
4T4-11	0.161	0.001	0.80	1.33	0.011	1.89	0.042	8.9	18.7	19.1	5.9	18.3	19.1	23
4T4-12	0.115	0.001	0.58	0.97	0.010	1.37	0.041	7.1	14.5	13.4	4.4	14.0	14.7	18.2
4T4-13	-	-	-	-	-	-	-	-	2.7	3.8	1.12	4.0	4.1	4.5
4T4-14	-	-	-	-	-	-	-	-	7.0	7.0	2.0	7.4	7.0	8.1
4T4-15	-	-	-	-	-	-	-	-	11.9	12.0	3.4	11.5	12.1	13.2
4T4-16	-	-	-	-	-	-	-	-	18	14.6	5.2	14.7	15.8	20
4T4-17	-	-	-	-	-	-	-	-	14.3	13.6	4.3	13.8	14.9	18.7
4T4-18	-	-	-	-	-	-	-	-	16.8	15.7	5.0	15.8	16.3	19.6
4T4-19	-	-	-	-	-	-	-	-	9.8	9.1	2.8	9.7	10.3	10.9
4T4-20	-	-	-	-	-	-	-	-	5.9	5.4	1.76	5.9	6.0	6.3
4S1-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/
4S2-1	-	-	-	-	<0.001	<0.001	0.001	<0.001	0.002	0.001	/	0.002	0.002	/
4S3-1	-	-	-	-	/	/	/	/	/	/	/	/	/	/

NS = north-south antenna.
EW = east-west antenna.
NEW = northern EW antenna element.
SEW = southern EW antenna element.
B = NS + EW antennas, standard phasing.
EX = extrapolated data.

\- = measurement point not established.
/ = measurement not taken.
* = data cannot be extrapolated.

TABLE D-9. 1993 PAIRED SITE EM FIELD INTENSITY RATIOS
Upland Flora and Soil Microflora Studies

Compared Sites	Air Electric Field				Earth Electric Field				Magnetic Flux Density			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
4T2PIN/4C1PIN	92	92	92	1.00	740	240	1110	3.1 - 16.4	1870	1870	1400	0.50 -11.0
4T4PIN/4C1PIN	43	43	43	1.00	400	126	590	3.8 - 210	870	1300	650	0.50 -11.0
4T2HDW/4C1HDW	87	87	87	1.00	1150	220	1290	5.1 - 13.5	1800	1830	1800	0.67 - 2.5
4T2HER/4C1HER	101	101	101	1.00	850	260	1140	3.4 - 5.8	1650	1650	1650	1.00 - 1.50

R1: T(76)/C(76)
R2: T(76)/T(60)
R3: T(76)/C(60)
R4: T(60)/C(60)

T(76) = ELF Communications System EM fields at the treatment site.
C(76) = ELF Communications System EM fields at the control site.
T(60) = ambient EM fields at the treatment site.
C(60) = ambient EM fields at the control site.

TABLE D-10. 1990 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 1 of 2)

Test Point	Measurement Date												Summary Statistics		
	6/28	7/10	7/24	8/7	8/21	9/4	9/18	10/2	10/22	11/7	12/5	12/21	Mean	SD	Coeff. of Variab.
4T2-3	140	135	139	145	142	141	139	141	143	147	153	157	144	6.0	0.042
4T2-4	129	128	124	125	126	127	126	126	126	125	120	121	125	2.5	0.020
4T2-5	105	99	97	94	102	99	104	105	111	108	110	106	103	5.0	0.049
4T2-6	101	100	96	97	100	94	96	97	106	104	104	105	100	3.9	0.039
4T2-7	89	86	84	82	80	84	81	85	87	87	88	83	85	2.7	0.032
4T2-8	135	130	142	143	132	138	133	137	141	143	141	145	138	4.7	0.034
4T2-9	125	122	119	116	120	118	117	119	122	122	136	141	123	7.4	0.060
4T2-10	91	87	88	88	87	89	88	92	97	95	96	98	91	4.0	0.043
4T2-11	170	168	160	158	168	165	168	168	177	171	123	125	160	16.8	0.105
4T2-12	114	144	113	114	110	110	106	108	114	116	154	163	122	18.8	0.154
4T2-13	144	142	144	145	144	146	146	143	147	146	156	160	147	5.2	0.035
4T2-14	121	115	117	113	118	117	122	124	127	126	122	125	121	4.3	0.036
4T2-16	91	88	85	81	90	91	90	96	97	99	94	95	91	5.0	0.054
4T2-19	107	106	106	103	106	105	106	106	107	107	105	106	106	1.10	0.010
4T2-20	107	107	102	108	107	105	106	107	111	110	114	121	109	4.7	0.043
4T2-21	143	139	122	132	139	142	139	140	149	144	141	144	140	6.6	0.047
4T2-22	98	92	91	85	93	86	89	93	90	89	85	85	90	3.9	0.043
4T2-23	114	108	109	107	112	109	115	115	126	122	113	115	114	5.4	0.047
4T2-24	120	121	114	112	117	117	120	123	127	126	128	123	121	4.8	0.040
4T2-25	115		117	121	116	114	115	114	118	120	129	129	119	5.2	0.044
4T2-26	210	200	200	210	210	199	198	197	210	220	230	220	210	9.4	0.045
4T2-27	118	112	124	130	119	116	115	116	129	133	124	131	122	6.9	0.056
4T2-28	151	151	153	157	152	153	152	153	149	151	152	149	152	2.0	0.013
4T2-29	55	55	61	63	53	53	54	53	53	59	53	54	56	3.4	0.060
4T2-30	106	105	113	122	110	107	112	113	115	124	120	122	114	6.3	0.055
4T2-31	94	96	98	99	99	100	101	100	102	102	103	104	100	2.8	0.028
4T2-32	75	73	73	72	74	74	75	74	75	73	72	75	74	1.10	0.015

TABLE D-10. 1990 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 2 of 2)

Test Point	Measurement Date												Summary Statistics		
	6/28	7/10	7/24	8/7	8/21	9/4	9/18	10/2	10/22	11/7	12/5	12/21	Mean	SD	Coeff. of Variab.
4T4-4	31	29	27	28	31	31	32	32	12	9	8.7	8.3	23	9.9	0.42
4T4-5	1670	1800	1830	1950	2100	2000	2000	1980	1720	1740	1980	1910	1900	134	0.071
4T4-6	117	115	115	125	136	138	141	143	148	140	142	140	133	11.4	0.086
4T4-7	135	132	130	132	137	135	137	139	144	146	145	149	138	6.0	0.043
4T4-8	113	108	105	106	109	105	108	109	112	113	109	111	109	2.7	0.025
4T4-9	42	42	42	43	42	43	43	44	18	20	20	22	35	10.7	0.31
4T4-10	32	30	30	30	30	29	32	33	35	37	37	37	33	3.0	0.090
4T4-11	1890	1940	2200	2300	2000	2100	2000	2000	2200	2200	2400	2500	2200	185	0.086
4T4-12	1600	1610	1700	1820	1850	1820	1900	1960	1820	1770	1820	1860	1790	104	0.058
4T4-21	109	107	91	97	122	127	131	134	146	135	132	136	122	16.5	0.135
4T4-22	148	137	139	148	153	154	159	169	177	174	170	165	158	12.8	0.081
4T4-23	330	340	330	350	380	370	390	400	410	380	370	390	370	25	0.069
4T4-24	360	360	340	340	390	380	410	430	430	420	420	420	390	32	0.081

Table D-11. 1991 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 1 of 2)

Test Point	Measurement Date																	Summary Statistics*		
						NS Antenna Only														
	1/4	1/18	2/19	3/18	4/25	5/29	6/21	7/8	7/25	8/16	8/28	9/9	9/30	10/11	10/23	11/8	12/6	Mean	SD	Coeff. of Variab.
4T2-3	147	144	146	153	152	48	49	49	153	159	160	150	150	148	149	149	140	150	5.1	0.034
4T2-4	112	117	112	128	131	44	44	43	135	136	138	139	136	130	135	124	129	129	8.9	0.069
4T2-5	108	111	132	130	111	35	34	35	118	112	108	118	120	120	119	122	122	118	7.1	0.061
4T2-6	112	119	113	112	109	38	37	40	109	121	120	112	113	116	114	114	116	114	3.6	0.031
4T2-7	95	101	102	97	97	27	26	26	83	84	84	87	90	89	91	90	93	92	5.9	0.065
4T2-8	149	150	150	146	147	43	42					137	134	139	140	144	153	145	5.9	0.041
4T2-9	137	134	141	138	128	37	38						165	164	156		140	145	12.7	0.088
4T2-10	100	99	98	101	100	35	35	35	96	102	103	95	103	103	105	103	102	101	2.8	0.028
4T2-11	139	131	136	128	167	50	41	55	173	144	106	167	166	165	162	172	119	148	21	0.143
4T2-12	161	162	165	151	132	39	45	39	124	131	132	129	120	123	124	136	160	139	16.1	0.115
4T2-13	180	169	167	149	139	41	43	41	150	149	146	148	147	149	150	149	149	153	10.6	0.070
4T2-14	113	121	119	126	131	39	39	39	128	128	133	127	133	130	135	123	128	127	5.8	0.046
4T2-15										58	60	65	66	64	65	63	59	63	2.9	0.046
4T2-16	81	85	87	100	101	33	34					108	118	114	120		100	101	13.1	0.129
4T2-17										99	92	111	109	111	111	111	100	106	7.0	0.066
4T2-18										118	116	112	108	110	110	110	103	111	4.3	0.039
4T2-19	98	103	99	106	104	33	33					107	116	101	108	124	103	106	7.3	0.069
4T2-20	129	122	123	121	117	39	39	38	116	113	114	112	112	114	114	113	106	116	5.6	0.048
4T2-21	141	128	135	140	145	57	52	54	144	135	82	140	131	130	127	132	120	131	15.1	0.116
4T2-22	86	89	94	91	109	43	40	43	98	86	86	99	104	94	97	88	94	94	6.7	0.072
4T2-23	106	107	108	120	117	40	35	39	116	116	114	129	129	127	129	123	107	118	8.4	0.071
4T2-24	121	130	132	133	133	37	36	36	122	115	120	124	124	125	126	118	124	125	5.4	0.043
4T2-25	138	135	132	125	107	28	15	4.5	88	69	76	57	61	65	63	124	103	96	30	0.31
4T2-26	250	240	230	220	230	67	62			200	192	220	210	210	210	240	240	220	15.8	0.071
4T2-27	149	146	146	134	138	37	30	37	129	135	131	122	126	132	130	155	130	136	9.2	0.068
4T2-28	178	168	164	154	153	52	55	54	162	167	155	156	153	157	153	153	150	159	7.6	0.048
4T2-29	70	70	78	73	72	15	14	15	64	66	66	54	54	58	56	64	58	65	7.3	0.114
4T2-30	130	129	131	124	128	40	38	40	116	125	67	107	114	121	120	132	120	119	16.0	0.134
4T2-31	103	104	105	104	98	37	39	38	106	97	91	108	108	107	109	103	100	103	4.9	0.047
4T2-32	58	63	61	77	80	28	28	28	76	74	74	82	79	77	80	76	84	74	7.7	0.104
4T2-33										114	138	116	116	114	117	126	122	120	7.7	0.064
4T2-34										97	100	118	110	111	112	114	119	110	7.4	0.067
4T2-35											162	155	155	161	158	179	163	162	7.6	0.047
4T2-36											128	142	140	136	135	136	142	137	4.6	0.033

Table D-11. 1991 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 2 of 2)

Test Point	Measurement Date																	Summary Statistics*		
						NS Antenna Only														
	1/4	1/18	2/19	3/18	4/25	5/29	6/21	7/8	7/25	8/16	8/28	9/9	9/30	10/11	10/23	11/8	12/6	Mean	SD	Coeff. of Variab.
4T4-4	6.8	7.1	8.3	10.3	9.2	10.6	9.9	10.4	11.1	11.3	11.5	12.8	12.6	12	13	12	11	10.6	2.0	0.185
4T4-5	2100	2100	2200	2200	1850	480	480	410	1780	1780	1850	1910	1900	1900	1850	1460	1580	1890	210	0.109
4T4-6	131	131	135	135	100	32	29	30	123	125	133	140	141	143	141	132	110	130	11.8	0.091
4T4-7	136	147	135	155	134	37	36										145	142	7.7	0.054
4T4-8	108	112	109	115	108	30	29	29	110	102	102	105	105	108	108	112	110	108	3.6	0.033
4T4-9	25	25	27	26	22	8.0	7.1	7.8	18.2	17.9	18.5	17.9	18.6	19	19	16	19	21	3.5	0.168
4T4-10	37	36	33	27	30	9.4	8.6	9.0	32	31	24	32	33	34	34	36	30	32	3.5	0.109
4T4-11	2600	2800	3200	2900	2400	550	550	480	2000	2200	2400	2100	2100	2100	2200	1790	2000	2300	390	0.167
4T4-12	2500	2300	2600	2700	1890	470	450	380	1550	1520	1580	1700	1800	1900	1830	1400	1520	1910	420	0.22
4T4-13													76	79				78	1.5	0.019
4T4-14												260	220	230	230	200	270	310	128	0.42
4T4-15										640	850	790	790	790	800	710	750	760	60	0.079
4T4-16										3500	3600	3100	3100	3200	3300	3400	3600	3300	194	0.058
4T4-18										4100	4400	4100	4200	4400	4400	4500	5000	4400	270	0.062
4T4-19												750	780	820	840	710	700	770	55	0.072
4T4-20																	220	220	0.0	0.0
4T4-21	128	123	120	149	92	39	34	33	113	89	100	124	130	128	130	111	98	117	16.5	0.141
4T4-22	154	148	143	161	123	52	44	46	133	149	152	156	152	157	160	151	129	148	11.2	0.076
4T4-23	390	380	400	390	310	91	88	83	340	370	390	400	390	400	400	340	320	370	30	0.081
4T4-24	450	440	450	470	350	115	104	100	370	350	360	410	430	430	430	310	370	400	49	0.121

*Summary statistics exclude data measured during solo operation of the NS antenna.

Table D-12. 1992 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 1 of 2)

Test Point	Measurement Date: NS Antenna Only															Summary Statistics*		
	1/3	2/5	3/4	4/1	4/27	5/29	7/8	7/22	8/5	8/19	9/2	9/16	10/5	10/14	11/9	12/7	Mean	SD	Coeff. of Variab.
4T2-3	45	40	40	132	153	162	156	155	156	149	148	142	154	150	136	130	148	9.6	0.065
4T2-4	41	40	43	126	137	142	137	142	141	141	150	155	148	150	127	122	140	9.6	0.069
4T2-5	35	32	34	123	126	129	133	137	130	138	137	136	139	140	133	123	133	5.7	0.043
4T2-6	39	38	40	115	117	112	116	112	114	111	110	109	114	112	102	103	111	4.4	0.039
4T2-7	29	28	31	100	95	90	90	88	85	86	84	86	87	88	85	80	88	4.9	0.055
4T2-8	45	47	49	146	151	150	146	144	155	146	145	143	153	150	141	141	147	4.3	0.029
4T2-9	42	45	45	144	139	135	134	138	135	135	135	133	140	137	132	139	137	3.2	0.023
4T2-10	38	36	38	108	111	103	103	100	94	92	91	93	97	95	80	82	96	8.7	0.091
4T2-11	36	35	35	113	152	157	175	180	173	180	174	179	182	180	110	107	159	28	0.177
4T2-12	52	53	52	157	127	122	121	119	124	121	123	115	125	123	142	144	128	11.6	0.091
4T2-13	41	42	43	149	148	149	148	134	155	152	155	151	151	148	146	144	148	5.2	0.035
4T2-14	38	39	40	133	129	135	139	137	137	132	132	131	133	132	124	120	132	5.0	0.038
4T2-15	26	27	28	65	67	65	69	70	68	69	69	70	71	69	59	56	67	4.3	0.065
4T2-16	34	34	35	109	105	104	104	101	102	107	108	112	109	111	96	86	104	6.7	0.065
4T2-17	31	28	28	100	106	106	108	111	110	109	110	108	113	112	103	95	107	4.9	0.046
4T2-18	30	29	32	112	106	110	107	108	110	105	106	103	105	103	96	99	105	4.3	0.041
4T2-19	33	33	32	107	107	105	107	108	99	107	108	111	109	107	101	97	106	3.9	0.037
4T2-20	37	42	43	104	114	123	117	119	120	115	116	114	119	119	106	115	115	5.1	0.045
4T2-21	45	48	50	128	124	118	131	133	127	136	134	139	136	138	111	108	128	9.7	0.076
4T2-22	37	39	40	94	95	98	103	104	93	100	98	103	99	97	78	72	95	9.2	0.097
4T2-23	35	33	37	118	123	126	126	135	126	134	130	136	131	133	111	98	125	10.4	0.083
4T2-24	36	36	39	127	140	135	128	128	124	124	124	126	129	128	121	115	127	5.9	0.046
4T2-25	20	40	39	129	125	126	126	125	127	125	124	120	129	124	120	122	125	2.7	0.022
4T2-26	73	78	80	230	240	240	230	230	230	220	220	210	230	220	200	210	220	11.5	0.051
4T2-27	38	42	41	130	153	148	141	140	147	139	133	132	150	145	117	125	138	10.2	0.073
4T2-28	54	54	54	150	144	128	136	135	153	142	143	140	157	146	124	130	141	9.4	0.067
4T2-29	17.2	19.2	19.1	61	73	75	67	66	72	62	61	58	63	60	45	61	63	7.4	0.117
4T2-30	44	47	47	125	142	140	131	128	139	126	126	123	136	130	105	113	128	10.1	0.079
4T2-31	37	37	38	104	105	104	105	107	105	103	105	103	105	104	88	87	102	6.2	0.061
4T2-32	30	30	30	89	84	76	77	79	73	74	78	82	77	79	71	69	78	5.2	0.067
4T2-33	44	45	45	118	119	119	112	110	109	110	109	108	112	112	97	98	110	6.5	0.059
4T2-34	42	46	48	131	130	122	117	118	115	114	115	115	120	118	101	102	117	8.3	0.071
4T2-35	55	54	54	156	163	165	163	167	164	164	164	158	171	164	146	140	160	8.3	0.052
4T2-36	48	50	52	150	145	141	136	139	137	135	136	140	137	136	121	120	136	7.9	0.058

Table D-12. 1992 76 Hz EARTH ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 2 of 2)

Test Point	NS Antenna Only			Measurement Date													Summary Statistics*		
	1/3	2/5	3/4	4/1	4/27	5/29	7/8	7/22	8/5	8/19	9/2	9/16	10/5	10/14	11/9	12/7	Mean	SD	Coeff. of Variab.
4T4-4	9.2	8.4	9.1	10	11	11	12	12.4	11.4	12	12	13	13	12	36	35	15.4	8.6	0.56
4T4-5	500	550	580	2000	1980	1900	1870	1810	1830	1700	1730	1730	1620	1580	1340	1350	1730	200	0.117
4T4-6	29	31	36	129	98	115	133	136	136	140	144	145	150	146	139	108	132	15.2	0.115
4T4-7	31	33	64	130	119	126	139	141	134	135	136	138	139	139	143	124	134	7.0	0.052
4T4-8	28	28	27	115	109	113	117	117	115	113	113	113	115	114	119	113	114	2.4	0.021
4T4-9	7.3	8.1	8.4	19	23	21	15.9	16	17.2	16	16.5	15.7	15.1	16.2	61	65	24	16.6	0.68
4T4-10	8.7	9.2	10.4	33	25	26	31	32	30	30	31	31	33	33	19.4	16.1	29	5.2	0.182
4T4-11	670	720	770	2600	2500	2300	2200	2000	2200	2000	2000	2000	2100	2000	1710	1880	2100	230	0.111
4T4-12	520	580	620	2100	1870	1900	1710	1670	1720	1660	1670	1700	1690	1630	1290	1400	1690	195	0.115
4T4-13	25	19	168	54	30	42	58	59	55	59	60	64	64	63	39	31	52	11.8	0.23
4T4-14	85	94	101	380	230	290	320	320	330	310	330	330	330	320	240	200	300	48	0.159
4T4-15	230	280	300	980	770	820	870	840	840	810	830	850	850	830	660	650	820	82	0.101
4T4-16	1170	1260	1220	4200	4200	3600	3200	3100	3900	3100	3200	3000	3000	3000	2700	3500	3400	460	0.138
4T4-18	1590	1890	1890	5100	5000	4500	3800	3700	4500	3600	3700	3600	3700	3700	3300	4300	4000	550	0.137
4T4-19	210	220	22	880	780	850	860	820	790	790	790	820	830	810	700	610	790	68	0.086
4T4-20	50	48	94	178	160	194	230	230	230	230	240	240	240	240	220	167	220	29	0.132
4T4-21	31	34	37	124	83	108	130	131	112	124	126	135	134	134	90	60	115	23	0.197
4T4-22	41	44	51	163	101	140	168	160	145	150	148	148	158	154	108	76	140	26	0.189
4T4-23	86	95	102	380	310	370	410	400	400	400	400	410	420	400	360	310	380	35	0.091
4T4-24	106	119	134	450	340	400	430	430	400	420	420	440	430	420	360	310	400	40	0.100

*Summary statistics exclude data measured during solo operation of the NS antenna.

Table D-13. 1993 76 Hz LONGITUDINAL ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 1 of 2)

Test Point	Measurement Date																Summary Statistics*		
	1/13	2/15	3/24	4/23	5/10	5/26	6/9	6/21	7/7	7/19	8/2	8/16	9/1	9/13	9/27	11/10	Mean	SD	Coeff. of Variab.
4T2-3	116	108	101	128	136	138	135	135	134	137	132	129	128	127	130	130	128	10.2	0.080
4T2-4	122	120	128	119	123	126	124	123	129	128	114	129	124	128	118	119	123	4.4	0.036
4T2-5	116	114	111	127	130	131	132	135	130	128	120	125	121	123	130	133	125	7.0	0.056
4T2-6	106	102	106	104	103	100	99	102	99	102	103	100	95	96	100	98	101	3.1	0.031
4T2-7	89	93	106	91	86	85	85	85	83	83	79	82	82	83	83	86	86	6.1	0.071
4T2-8	135	88	139	136	136	139	134	134	133	137	140	134	133	133	137	138	133	11.8	0.089
4T2-9	136	145	145	132	132	127	127	131	131	133	117	134	135	134	133	130	133	6.4	0.048
4T2-10	82	82	87	81	82	83	83	85	82	83	80	82	82	83	83	86	83	1.73	0.021
4T2-11	103	104	106	102	101	104	102	106	105	105	104	106	105	104	109	108	105	2.1	0.020
4T2-12	143	149	148	140	140	134	131	131	135	137	131	136	135	130	138	144	138	5.8	0.042
4T2-13	139	146	151	142	150	150	151	154	158	158	153	162	160	162	160	154	153	6.6	0.043
4T2-14	127	132	131	116	121	122	124	123	125	128	123	126	121	128	125	126	125	3.9	0.031
4T2-15	56	60	58	60	56	56	58	58	56	58	53	58	56	58	57	58	57	1.69	0.030
4T2-16	90	87	88	86	91	92	96	89	93	89	82	92	92	94	91	93	90	3.3	0.037
4T2-17	90	84	83	99	96	98	93	95	94	98	100	101	101	102	101	103	96	5.9	0.061
4T2-18	101	98	109	89	97	99	95	95	102	108	109	109	109	107	104	98	102	6.1	0.060
4T2-19	106	104	103	94	94	96	96	97	97	95	92	95	94	96	96	100	97	3.9	0.040
4T2-20	130	115	117	106	110	110	109	109	108	108	103	105	106	108	106	104	110	6.3	0.057
4T2-21	108	112	106	111	112	111	111	112	106	105	93	102	98	98	97	103	105	6.0	0.057
4T2-22	70	69	72	84	86	83	84	85	78	72	57	71	64	68	69	74	74	8.2	0.111
4T2-23	99	97	95	103	102	105	102	101	98	101	98	102	97	97	101	103	100	2.7	0.027
4T2-24	111	112	131	121	130	130	131	132	130	125	120	124	122	123	125	124	124	6.2	0.050
4T2-25	126	131	132	125	121	122	152	141	135	142	143	150	176	186	162	140	143	18.2	0.127
4T2-26	213	220	240	210	200	199	198	199	199	199	200	194	197	188	200	200	204	11.9	0.058
4T2-27	130	131	144	109	108	110	90	89	89	99	107	90	99	89	99	109	106	16.2	0.153
4T2-28	132	129	136	127	128	128	129	132	135	140	138	140	137	139	144	134	134	5.0	0.037
4T2-29	65	68	74	57	56	55	54	49	56	62	65	56	57	55	54	48	58	6.7	0.116
4T2-30	118	119	123	102	100	102	169	172	173	170	170	166	169	165	169	170	147	29	0.197
4T2-31	88	92	96	88	86	87	88	89	88	89	84	92	90	88	88	90	89	2.7	0.030
4T2-32	67	77	75	77	77	73	75	75	70	69	63	69	67	69	65	68	71	4.4	0.062
4T2-33	99	103	109	96	98	97	96	96	92	92	87	87	93	93	95	100	96	5.4	0.056
4T2-34	106	116	143	104	105	106	103	102	96	97	96	97	102	101	100	106	105	11.0	0.105
4T2-35	137	133	127	138	141	143	139	140	139	138	129	138	137	139	143	141	138	4.3	0.031
4T2-36	124	139	168	127	128	128	126	124	122	123	120	129	127	127	120	119	128	11.3	0.088

Table D-13. 1993 76 Hz LONGITUDINAL ELECTRIC FIELD INTENSITIES (mV/m)
Upland Flora and Soil Microflora Antenna Site Fixed Test Points
(page 2 of 2)

Test Point	Measurement Date																Summary Statistics*		
	1/13	2/15	3/24	4/23	5/10	5/26	6/9	6/21	7/7	7/19	8/2	8/16	9/1	9/13	9/27	11/10	Mean	SD	Coeff. of Variab.
4T4-4	37	38	38	34	35	35	36	36	35	35	37	38	38	38	36	36	36	1.32	0.037
4T4-5	1630	1800	1950	1640	1480	1550	1430	1470	1450	1510	1570	1650	1630	1700	1430	1410	1580	144	0.091
4T4-6	107	109	117	111	101	110	111	116	109	114	122	134	136	130	138	137	119	11.8	0.099
4T4-7	133	130	148	129	127	123	129	132	128	132	130	134	137	136	136	138	133	5.6	0.042
4T4-8	114	112	111	119	115	118	119	122	120	125	120	120	114	116	116	120	118	3.7	0.031
4T4-9	73	80	77	60	63	64	62	62	62	66	72	69	69	67	67	66	67	5.5	0.082
4T4-10	17	16.3	19.2	16.8	15.3	14.6	14.4	15.1	14.7	14.1	16.8	14.9	14.4	15.2	17.4	19	16.0	1.56	0.098
4T4-11	2000	2300	2500	1990	1910	1920	1770	1750	1760	1890	2200	2000	2000	2000	1900	1860	1980	195	0.098
4T4-12	1610	1730	2100	1500	1410	1540	1370	1390	1290	1310	1450	1390	1420	1500	1440	1360	1490	192	0.129
4T4-13	38	40	41	35	31	31	32	32	32	34	31	38	39	40	38	41	36	3.8	0.106
4T4-14	230	250	220	210	180	198	200	210	210	220	240	260	250	270	250	240	230	25	0.109
4T4-15	820	970	1000	710	650	720	660	690	650	680	720	700	700	700	710	680	740	102	0.138
4T4-16	3800	3900	4800	3200	3000	2900	2600	2500	2700	3000	3700	3000	3200	3200	2800	2900	3200	570	0.178
4T4-18	4700	5900	7000	3800	3600	3500	3200	3000	3300	3400	4300	3400	3500	3500	3100	3500	3900	1060	0.270
4T4-19	660	710	740	710	640	700	670	690	660	660	650	650	640	630	680	690	670	30	0.045
4T4-20	160	156	172	170	160	169	169	176	171	181	183	198	196	210	210	210	181	18.0	0.099
4T4-21	68	72	87	74	58	69	70	75	67	68	60	78	80	83	85	85	74	8.5	0.115
4T4-22	91	105	110	91	75	84	79	90	85	/	93	97	99	106	113	113	95	11.7	0.123
4T4-23	330	350	340	341	310	340	340	340	340	350	390	400	400	400	400	370	360	29	0.081
4T4-24	360	400	480	330	307	350	330	350	330	350	340	380	380	390	390	380	370	39	0.105

* Summary statistics exclude data measured during solo operation of the NS antenna.

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)*	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
01-Jan-93	0.00	23.98	B	MSK	76	150	99
02-Jan-93	0.00	23.98	B	MSK	76	150	99
03-Jan-93	0.00	21.33	B	MSK	76	150	99
03-Jan-93	21.33	23.98	B	MSK	76	150	99
04-Jan-93	0.00	23.98	B	MSK	76	150	99
05-Jan-93	0.00	21.16	B	MSK	76	150	99
05-Jan-93	21.16	23.98	B	MSK	76	150	99
06-Jan-93	0.00	23.98	B	MSK	76	150	99
07-Jan-93	0.00	14.00	B	MSK	76	150	99
07-Jan-93	19.91	23.98	B	MSK	76	150	99
08-Jan-93	0.00	21.75	B	MSK	76	150	99
08-Jan-93	21.75	23.98	B	MSK	76	150	99
09-Jan-93	0.00	0.68	B	MSK	76	150	99
09-Jan-93	0.68	23.98	B	MSK	76	150	99
10-Jan-93	0.00	23.98	B	MSK	76	150	99
11-Jan-93	0.00	23.98	B	MSK	76	150	99
12-Jan-93	0.00	14.13	B	MSK	76	150	99
12-Jan-93	19.83	23.98	B	MSK	76	150	99
13-Jan-93	0.00	13.75	B	MSK	76	150	99
13-Jan-93	13.75	22.13	B	MSK	76	150	99
13-Jan-93	22.13	23.98	B	MSK	76	150	99
14-Jan-93	0.00	14.00	B	MSK	76	150	99
14-Jan-93	19.98	23.98	B	MSK	76	150	99
15-Jan-93	0.00	23.98	B	MSK	76	150	99
16-Jan-93	0.00	23.98	B	MSK	76	150	99
17-Jan-93	0.00	23.98	B	MSK	76	150	99
18-Jan-93	0.00	23.98	B	MSK	76	150	99
19-Jan-93	0.00	14.00	B	MSK	76	150	99
19-Jan-93	14.33	14.36	NS	MSK	76	150	
19-Jan-93	19.76	23.98	B	MSK	76	150	99
20-Jan-93	0.00	13.66	B	MSK	76	150	99
20-Jan-93	13.66	22.00	B	MSK	76	150	99
20-Jan-93	22.00	23.98	B	MSK	76	150	99
21-Jan-93	0.00	14.00	B	MSK	76	150	99
21-Jan-93	19.75	23.98	B	MSK	76	150	99
22-Jan-93	0.00	23.98	B	MSK	76	150	99
23-Jan-93	0.00	23.98	B	MSK	76	150	99
24-Jan-93	0.00	23.98	B	MSK	76	150	99
25-Jan-93	0.00	23.98	B	MSK	76	150	99
26-Jan-93	0.00	14.00	B	MSK	76	150	99
26-Jan-93	19.83	23.98	B	MSK	76	150	99
27-Jan-93	0.00	13.50	B	MSK	76	150	99
27-Jan-93	13.50	22.13	B	MSK	76	150	99
27-Jan-93	22.13	23.98	B	MSK	76	150	99
28-Jan-93	0.00	14.00	B	MSK	76	150	99
28-Jan-93	19.75	23.98	B	MSK	76	150	99
29-Jan-93	0.00	23.98	B	MSK	76	150	99

* GMT = CST + 6 HOURS

GMT = CDT + 5 HOURS

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
30-Jan-93	0.00	23.98	B	MSK	76	150	99
31-Jan-93	0.00	23.98	B	MSK	76	150	99
01-Feb-93	0.00	13.85	B	MSK	76	150	99
01-Feb-93	13.85	23.68	B	MSK	76	150	99
01-Feb-93	23.68	23.98	B	MSK	76	150	99
02-Feb-93	0.00	14.01	B	MSK	76	150	99
02-Feb-93	14.01	23.05	B	MSK	76	150	99
02-Feb-93	23.05	23.98	B	MSK	76	150	99
03-Feb-93	0.00	13.60	B	MSK	76	150	99
03-Feb-93	13.60	23.36	B	MSK	76	150	99
03-Feb-93	23.36	23.98	B	MSK	76	150	99
04-Feb-93	0.00	13.83	B	MSK	76	150	99
04-Feb-93	13.83	23.05	B	MSK	76	150	99
04-Feb-93	23.05	23.98	B	MSK	76	150	99
05-Feb-93	0.00	13.90	B	MSK	76	150	99
05-Feb-93	13.90	23.06	B	MSK	76	150	99
05-Feb-93	23.06	23.98	B	MSK	76	150	99
06-Feb-93	0.00	20.78	B	MSK	76	150	99
06-Feb-93	20.78	23.01	B	MSK	76	150	99
06-Feb-93	23.01	23.98	B	MSK	76	150	99
07-Feb-93	0.00	23.98	B	MSK	76	150	99
08-Feb-93	0.00	13.83	B	MSK	76	150	99
08-Feb-93	13.83	22.50	B	MSK	76	150	99
08-Feb-93	22.50	23.98	B	MSK	76	150	99
09-Feb-93	0.00	13.83	B	MSK	76	150	99
09-Feb-93	13.83	23.98	B	MSK	76	150	99
10-Feb-93	0.00	23.98	B	MSK	76	150	99
11-Feb-93	0.00	22.86	B	MSK	76	150	99
11-Feb-93	22.86	23.98	B	MSK	76	150	99
12-Feb-93	0.00	13.81	B	MSK	76	150	99
12-Feb-93	13.81	23.25	B	MSK	76	150	99
12-Feb-93	23.25	23.98	B	MSK	76	150	99
13-Feb-93	0.00	15.41	B	MSK	76	150	99
13-Feb-93	15.66	23.73	B	MSK	76	150	99
13-Feb-93	23.73	23.98	B	MSK	76	150	99
14-Feb-93	0.00	2.50	B	MSK	76	150	99
14-Feb-93	2.50	23.98	B	MSK	76	150	99
15-Feb-93	0.00	23.98	B	MSK	76	150	99
16-Feb-93	0.00	14.00	B	MSK	76	150	99
16-Feb-93	19.86	23.98	B	MSK	76	150	99
17-Feb-93	0.00	13.81	B	MSK	76	150	99
17-Feb-93	13.81	22.00	B	MSK	76	150	99
17-Feb-93	22.00	23.98	B	MSK	76	150	99
18-Feb-93	0.00	14.05	B	MSK	76	150	99
18-Feb-93	19.83	23.98	B	MSK	76	150	99
19-Feb-93	0.00	14.00	B	MSK	76	150	99
19-Feb-93	19.78	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
20-Feb-93	0.00	23.98	B	MSK	76	150	99
21-Feb-93	0.00	23.98	B	MSK	76	150	99
22-Feb-93	0.00	23.98	B	MSK	76	150	99
23-Feb-93	0.00	14.00	B	MSK	76	150	99
23-Feb-93	19.75	23.98	B	MSK	76	150	99
24-Feb-93	0.00	13.26	B	MSK	76	150	99
24-Feb-93	13.26	22.55	B	MSK	76	150	99
24-Feb-93	22.55	23.98	B	MSK	76	150	99
25-Feb-93	0.00	14.00	B	MSK	76	150	99
25-Feb-93	19.75	23.98	B	MSK	76	150	99
26-Feb-93	0.00	14.00	B	MSK	76	150	99
26-Feb-93	19.83	23.98	B	MSK	76	150	99
27-Feb-93	0.00	23.98	B	MSK	76	150	99
28-Feb-93	0.00	23.98	B	MSK	76	150	99
01-Mar-93	0.00	23.98	B	MSK	76	150	99
02-Mar-93	0.00	6.28	B	MSK	76	150	99
02-Mar-93	6.28	13.71	B	MSK	76	150	99
02-Mar-93	13.71	14.00	B	MSK	76	150	99
02-Mar-93	19.86	20.93	B	MSK	76	150	99
02-Mar-93	20.93	23.98	B	MSK	76	150	99
03-Mar-93	0.00	22.00	B	MSK	76	150	99
03-Mar-93	22.00	23.98	B	MSK	76	150	99
04-Mar-93	0.00	14.00	B	MSK	76	150	99
04-Mar-93	19.75	23.98	B	MSK	76	150	99
05-Mar-93	0.00	23.98	B	MSK	76	150	99
06-Mar-93	0.00	23.98	B	MSK	76	150	99
07-Mar-93	0.00	23.98	B	MSK	76	150	99
08-Mar-93	0.00	23.98	B	MSK	76	150	99
09-Mar-93	0.00	14.00	B	MSK	76	150	99
09-Mar-93	20.41	22.51	B	MSK	76	150	99
09-Mar-93	22.51	23.98	B	MSK	76	150	99
10-Mar-93	0.00	23.98	B	MSK	76	150	99
11-Mar-93	0.00	14.00	B	MSK	76	150	99
11-Mar-93	19.75	23.98	B	MSK	76	150	99
12-Mar-93	0.00	23.98	B	MSK	76	150	99
13-Mar-93	0.00	23.98	B	MSK	76	150	99
14-Mar-93	0.00	23.98	B	MSK	76	150	99
15-Mar-93	0.00	23.98	B	MSK	76	150	99
16-Mar-93	0.00	14.00	B	MSK	76	150	99
16-Mar-93	19.76	20.28	B	MSK	76	150	99
16-Mar-93	20.28	22.33	B	MSK	76	150	99
16-Mar-93	22.33	23.98	B	MSK	76	150	99
17-Mar-93	0.00	13.66	B	MSK	76	150	99
17-Mar-93	13.66	22.01	B	MSK	76	150	99
17-Mar-93	22.01	23.98	B	MSK	76	150	99
18-Mar-93	0.00	14.00	B	MSK	76	150	99
18-Mar-93	19.76	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
19-Mar-93	0.00	23.98	B	MSK	76	150	99
20-Mar-93	0.00	23.98	B	MSK	76	150	99
21-Mar-93	0.00	23.98	B	MSK	76	150	99
22-Mar-93	0.00	23.98	B	MSK	76	150	99
23-Mar-93	0.00	14.00	B	MSK	76	150	99
23-Mar-93	19.90	23.98	B	MSK	76	150	99
24-Mar-93	0.00	13.43	B	MSK	76	150	99
24-Mar-93	13.43	22.00	B	MSK	76	150	99
24-Mar-93	22.00	23.98	B	MSK	76	150	99
25-Mar-93	0.00	14.01	B	MSK	76	150	99
25-Mar-93	19.83	23.98	B	MSK	76	150	99
26-Mar-93	0.00	23.98	B	MSK	76	150	99
27-Mar-93	0.00	23.98	B	MSK	76	150	99
28-Mar-93	0.00	23.98	B	MSK	76	150	99
29-Mar-93	0.00	23.98	B	MSK	76	150	99
30-Mar-93	0.00	14.00	B	MSK	76	150	99
30-Mar-93	19.93	23.98	B	MSK	76	150	99
31-Mar-93	0.00	13.58	B	MSK	76	150	99
31-Mar-93	13.58	22.33	B	MSK	76	150	99
31-Mar-93	22.33	23.98	B	MSK	76	150	99
01-Apr-93	0.00	13.00	B	MSK	76	150	99
01-Apr-93	18.86	23.98	B	MSK	76	150	99
02-Apr-93	0.00	23.98	B	MSK	76	150	99
03-Apr-93	0.00	23.98	B	MSK	76	150	99
04-Apr-93	0.00	23.98	B	MSK	76	150	99
05-Apr-93	0.00	23.98	B	MSK	76	150	99
06-Apr-93	0.00	13.00	B	MSK	76	150	99
06-Apr-93	18.75	23.98	B	MSK	76	150	99
07-Apr-93	0.00	12.66	B	MSK	76	150	99
07-Apr-93	12.66	23.98	B	MSK	76	150	99
08-Apr-93	0.00	0.12	B	MSK	76	150	99
08-Apr-93	0.12	9.20	B	MSK	76	150	99
08-Apr-93	9.20	12.93	B	MSK	76	150	99
08-Apr-93	12.93	13.00	B	MSK	76	150	99
08-Apr-93	18.75	19.26	B	MSK	76	150	99
08-Apr-93	19.26	23.98	B	MSK	76	150	99
09-Apr-93	0.00	23.98	B	MSK	76	150	99
10-Apr-93	0.00	23.98	B	MSK	76	150	99
11-Apr-93	0.00	23.98	B	MSK	76	150	99
12-Apr-93	0.00	21.53	B	MSK	76	150	99
12-Apr-93	21.53	23.98	B	MSK	76	150	99
13-Apr-93	0.00	4.78	B	MSK	76	150	99
13-Apr-93	4.92	13.00	B	MSK	76	150	99
13-Apr-93	18.75	23.98	B	MSK	76	150	99
14-Apr-93	0.00	12.80	B	MSK	76	150	99
14-Apr-93	12.80	21.05	B	MSK	76	150	99
14-Apr-93	21.05	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
15-Apr-93	0.00	13.00	B	MSK	76	150	99
15-Apr-93	18.76	23.98	B	MSK	76	150	99
16-Apr-93	0.00	23.98	B	MSK	76	150	99
17-Apr-93	0.00	23.98	B	MSK	76	150	99
18-Apr-93	0.00	23.98	B	MSK	76	150	99
19-Apr-93	0.00	23.98	B	MSK	76	150	99
20-Apr-93	0.00	13.00	B	MSK	76	150	99
20-Apr-93	18.90	23.98	B	MSK	76	150	99
21-Apr-93	0.00	12.63	B	MSK	76	150	99
21-Apr-93	12.63	21.95	B	MSK	76	150	99
21-Apr-93	21.95	23.98	B	MSK	76	150	99
22-Apr-93	0.00	13.00	B	MSK	76	150	99
22-Apr-93	18.83	23.98	B	MSK	76	150	99
23-Apr-93	0.00	23.98	B	MSK	76	150	99
24-Apr-93	0.00	12.25	B	MSK	76	150	99
24-Apr-93	12.25	20.30	B	MSK	76	150	99
24-Apr-93	20.30	20.33	NS	MSK	76	150	
24-Apr-93	20.33	20.40	B	MSK	76	150	99
24-Apr-93	20.40	20.48	NS	MSK	76	150	
24-Apr-93	20.48	20.55	B	MSK	76	150	99
24-Apr-93	20.55	20.58	NS	MSK	76	150	
24-Apr-93	20.58	20.63	B	MSK	76	150	99
24-Apr-93	20.63	20.66	NS	MSK	76	150	
24-Apr-93	20.66	22.00	B	MSK	76	150	99
24-Apr-93	22.00	23.98	B	MSK	76	150	99
25-Apr-93	0.00	23.98	B	MSK	76	150	99
26-Apr-93	0.00	23.98	B	MSK	76	150	99
27-Apr-93	0.00	13.00	B	MSK	76	150	99
27-Apr-93	18.75	23.98	B	MSK	76	150	99
28-Apr-93	0.00	12.68	B	MSK	76	150	99
28-Apr-93	12.68	23.98	B	MSK	76	150	99
29-Apr-93	0.00	13.00	B	MSK	76	150	99
29-Apr-93	18.75	19.18	B	MSK	76	150	99
29-Apr-93	19.18	23.98	B	MSK	76	150	99
30-Apr-93	0.00	23.98	B	MSK	76	150	99
01-May-93	0.00	23.98	B	MSK	76	150	99
02-May-93	0.00	23.98	B	MSK	76	150	99
03-May-93	0.00	23.98	B	MSK	76	150	99
04-May-93	0.00	13.00	B	MSK	76	150	99
04-May-93	18.78	23.98	B	MSK	76	150	99
05-May-93	0.00	12.76	B	MSK	76	150	99
05-May-93	12.76	21.48	B	MSK	76	150	99
05-May-93	21.48	23.98	B	MSK	76	150	99
06-May-93	0.00	3.08	B	MSK	76	150	99
06-May-93	3.33	11.73	B	MSK	76	150	99
06-May-93	11.73	13.00	B	MSK	76	150	99
06-May-93	18.75	18.80	EW	MSK	76	150	

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
06-May-93	18.80	23.98	B	MSK	76	150	99
07-May-93	0.00	23.98	B	MSK	76	150	99
08-May-93	0.00	21.50	B	MSK	76	150	99
08-May-93	21.50	23.98	B	MSK	76	150	99
09-May-93	0.00	3.53	B	MSK	76	150	99
09-May-93	3.53	17.26	B	MSK	76	150	99
09-May-93	17.26	22.21	B	MSK	76	150	99
09-May-93	22.21	23.98	B	MSK	76	150	99
10-May-93	0.00	19.86	B	MSK	76	150	99
10-May-93	21.30	23.98	B	MSK	76	150	99
11-May-93	0.00	13.01	B	MSK	76	150	99
11-May-93	18.86	18.96	B	MSK	76	150	99
11-May-93	18.96	23.98	B	MSK	76	150	99
12-May-93	0.00	12.75	B	MSK	76	150	99
12-May-93	12.75	21.38	B	MSK	76	150	99
12-May-93	21.38	23.98	B	MSK	76	150	99
13-May-93	0.00	13.00	B	MSK	76	150	99
13-May-93	13.08	13.11	NS	CW	76	150	
13-May-93	18.70	23.98	B	MSK	76	150	99
14-May-93	0.00	2.55	B	MSK	76	150	99
14-May-93	2.55	3.73	B	MSK	76	150	99
14-May-93	3.73	4.43	B	MSK	76	150	99
14-May-93	4.43	9.27	B	MSK	76	150	99
14-May-93	9.27	15.08	B	MSK	76	150	99
14-May-93	15.16	23.98	B	MSK	76	150	99
15-May-93	0.00	23.98	B	MSK	76	150	99
16-May-93	0.00	23.98	B	MSK	76	150	99
17-May-93	0.00	23.98	B	MSK	76	150	99
18-May-93	0.00	13.00	B	MSK	76	150	99
18-May-93	18.75	23.98	B	MSK	76	150	99
19-May-93	0.00	12.76	B	MSK	76	150	99
19-May-93	12.76	18.65	B	MSK	76	150	99
19-May-93	18.65	18.66	B	MSK	76	150	99
19-May-93	18.81	18.95	B	MSK	76	150	99
19-May-93	18.95	21.48	B	MSK	76	150	99
19-May-93	21.48	23.98	B	MSK	76	150	99
20-May-93	0.00	11.91	B	MSK	76	150	99
20-May-93	12.00	13.00	B	MSK	76	150	99
20-May-93	18.76	23.98	B	MSK	76	150	99
21-May-93	0.00	23.98	B	MSK	76	150	99
22-May-93	0.00	23.98	B	MSK	76	150	99
23-May-93	0.00	23.98	B	MSK	76	150	99
24-May-93	0.00	23.98	B	MSK	76	150	99
25-May-93	0.00	13.00	B	MSK	76	150	99
25-May-93	18.75	18.93	B	MSK	76	150	99
25-May-93	18.93	19.58	B	MSK	76	150	99
25-May-93	19.61	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
26-May-93	0.00	21.50	B	MSK	76	150	99
26-May-93	21.50	23.98	B	MSK	76	150	99
27-May-93	0.00	13.00	B	MSK	76	150	99
27-May-93	17.45	18.75	B	MSK	76	150	99
27-May-93	18.75	19.25	B	MSK	76	150	99
27-May-93	19.25	23.98	B	MSK	76	150	99
28-May-93	0.00	23.98	B	MSK	76	150	99
29-May-93	0.00	23.98	B	MSK	76	150	99
30-May-93	0.00	23.98	B	MSK	76	150	99
31-May-93	0.00	23.98	B	MSK	76	150	99
01-Jun-93	0.00	13.00	B	MSK	76	150	99
01-Jun-93	18.75	23.98	B	MSK	76	150	99
02-Jun-93	0.00	0.17	B	MSK	76	150	99
02-Jun-93	0.25	12.73	B	MSK	76	150	99
02-Jun-93	12.73	21.60	B	MSK	76	150	99
02-Jun-93	21.60	23.98	B	MSK	76	150	99
03-Jun-93	0.00	13.00	B	MSK	76	150	99
03-Jun-93	18.78	23.98	B	MSK	76	150	99
04-Jun-93	0.00	23.98	B	MSK	76	150	99
05-Jun-93	0.00	23.98	B	MSK	76	150	99
06-Jun-93	0.00	23.98	B	MSK	76	150	99
07-Jun-93	0.00	23.98	B	MSK	76	150	99
08-Jun-93	0.00	4.20	B	MSK	76	150	99
08-Jun-93	4.20	7.20	B	MSK	76	150	99
08-Jun-93	7.20	13.00	B	MSK	76	150	99
08-Jun-93	17.33	17.41	EW	MSK	76	150	
08-Jun-93	18.81	23.98	B	MSK	76	150	99
09-Jun-93	0.00	12.83	B	MSK	76	150	99
09-Jun-93	12.83	21.00	B	MSK	76	150	99
09-Jun-93	21.00	23.98	B	MSK	76	150	99
10-Jun-93	0.00	13.00	B	MSK	76	150	99
10-Jun-93	18.80	23.98	B	MSK	76	150	99
11-Jun-93	0.00	23.98	B	MSK	76	150	99
12-Jun-93	0.00	23.98	B	MSK	76	150	99
13-Jun-93	0.00	20.41	B	MSK	76	150	99
13-Jun-93	20.41	22.50	B	MSK	76	150	99
13-Jun-93	22.50	23.98	B	MSK	76	150	99
14-Jun-93	0.00	23.98	B	MSK	76	150	99
15-Jun-93	0.00	12.83	B	MSK	76	150	99
15-Jun-93	12.83	13.00	B	MSK	76	150	99
15-Jun-93	18.83	19.08	B	MSK	76	150	99
15-Jun-93	19.08	23.98	B	MSK	76	150	99
16-Jun-93	0.00	23.98	B	MSK	76	150	99
17-Jun-93	0.00	8.23	B	MSK	76	150	99
17-Jun-93	8.30	8.42	B	MSK	76	150	99
17-Jun-93	8.42	8.62	B	MSK	76	150	99
17-Jun-93	8.62	8.70	EW	MSK	76	150	

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
17-Jun-93	8.70	8.87	B	MSK	76	150	99
17-Jun-93	9.02	9.22	NS	MSK	76	150	
17-Jun-93	11.25	13.00	NS	MSK	76	150	
17-Jun-93	22.43	23.98	B	MSK	76	150	99
18-Jun-93	0.00	23.98	B	MSK	76	150	99
19-Jun-93	0.00	23.98	B	MSK	76	150	99
20-Jun-93	0.00	23.98	B	MSK	76	150	99
21-Jun-93	0.00	23.98	B	MSK	76	150	99
22-Jun-93	0.00	7.80	B	MSK	76	150	99
22-Jun-93	7.80	10.38	B	MSK	76	150	99
22-Jun-93	10.38	13.00	B	MSK	76	150	99
22-Jun-93	18.75	23.98	B	MSK	76	150	99
23-Jun-93	0.00	12.58	B	MSK	76	150	99
23-Jun-93	12.58	21.00	B	MSK	76	150	99
23-Jun-93	21.00	23.98	B	MSK	76	150	99
24-Jun-93	0.00	13.00	B	MSK	76	150	99
24-Jun-93	18.76	20.40	B	MSK	76	150	99
24-Jun-93	20.51	21.33	B	MSK	76	150	99
24-Jun-93	21.33	21.38	EW	MSK	76	150	
24-Jun-93	21.38	22.01	B	MSK	76	150	99
24-Jun-93	22.01	22.03	NS	MSK	76	150	
24-Jun-93	22.08	23.86	B	MSK	76	150	99
24-Jun-93	23.88	23.98	B	MSK	76	150	99
25-Jun-93	0.00	23.98	B	MSK	76	150	99
26-Jun-93	0.00	17.10	B	MSK	76	150	99
26-Jun-93	17.10	21.36	B	MSK	76	150	99
26-Jun-93	21.36	23.98	B	MSK	76	150	99
27-Jun-93	0.00	23.98	B	MSK	76	150	99
28-Jun-93	0.00	22.21	B	MSK	76	150	99
28-Jun-93	22.21	23.98	B	MSK	76	150	99
29-Jun-93	0.00	1.02	B	MSK	76	150	99
29-Jun-93	1.02	13.00	B	MSK	76	150	99
29-Jun-93	18.75	23.98	B	MSK	76	150	99
30-Jun-93	0.00	12.98	B	MSK	76	150	99
30-Jun-93	12.98	21.16	B	MSK	76	150	99
30-Jun-93	21.16	23.98	B	MSK	76	150	99
01-Jul-93	0.00	13.00	B	MSK	76	150	99
01-Jul-93	18.76	21.50	B	MSK	76	150	99
01-Jul-93	21.50	22.83	B	MSK	76	150	99
01-Jul-93	22.83	23.98	B	MSK	76	150	99
02-Jul-93	0.00	4.42	B	MSK	76	150	99
02-Jul-93	4.50	23.98	B	MSK	76	150	99
03-Jul-93	0.00	23.98	B	MSK	76	150	99
04-Jul-93	0.00	1.33	B	MSK	76	150	99
04-Jul-93	1.42	2.63	B	MSK	76	150	99
04-Jul-93	2.63	4.45	B	MSK	76	150	99
04-Jul-93	4.45	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
05-Jul-93	0.00	23.98	B	MSK	76	150	99
06-Jul-93	0.00	13.00	B	MSK	76	150	99
06-Jul-93	18.73	23.98	B	MSK	76	150	99
07-Jul-93	0.00	12.91	B	MSK	76	150	99
07-Jul-93	12.91	21.00	B	MSK	76	150	99
07-Jul-93	21.00	23.98	B	MSK	76	150	99
08-Jul-93	0.00	13.00	B	MSK	76	150	99
08-Jul-93	18.66	20.51	B	MSK	76	150	99
08-Jul-93	20.51	21.00	B	MSK	76	150	99
08-Jul-93	21.00	23.98	B	MSK	76	150	99
09-Jul-93	0.00	18.16	B	MSK	76	150	99
09-Jul-93	18.25	23.98	B	MSK	76	150	99
10-Jul-93	0.00	23.98	B	MSK	76	150	99
11-Jul-93	0.00	14.88	B	MSK	76	150	99
11-Jul-93	14.88	17.06	B	MSK	76	150	99
11-Jul-93	17.06	23.98	B	MSK	76	150	99
12-Jul-93	0.00	23.98	B	MSK	76	150	99
13-Jul-93	0.00	13.00	B	MSK	76	150	99
13-Jul-93	18.88	23.98	B	MSK	76	150	99
14-Jul-93	0.00	12.60	B	MSK	76	150	99
14-Jul-93	12.60	21.16	B	MSK	76	150	99
14-Jul-93	21.16	23.61	B	MSK	76	150	99
14-Jul-93	23.93	23.98	B	MSK	76	150	99
15-Jul-93	0.00	13.00	B	MSK	76	150	99
15-Jul-93	18.95	23.98	B	MSK	76	150	99
16-Jul-93	0.00	6.25	B	MSK	76	150	99
16-Jul-93	6.35	23.98	B	MSK	76	150	99
17-Jul-93	0.00	23.98	B	MSK	76	150	99
18-Jul-93	0.00	2.50	B	MSK	76	150	99
18-Jul-93	2.58	14.68	B	MSK	76	150	99
18-Jul-93	14.68	14.75	EW	MSK	76	150	
18-Jul-93	14.75	17.05	B	MSK	76	150	99
18-Jul-93	17.05	17.08	EW	MSK	76	150	
18-Jul-93	17.08	18.61	B	MSK	76	150	99
18-Jul-93	18.61	18.85	EW	MSK	76	150	
18-Jul-93	18.85	23.98	B	MSK	76	150	99
19-Jul-93	0.00	23.98	B	MSK	76	150	99
20-Jul-93	0.00	13.00	B	MSK	76	150	99
20-Jul-93	18.75	23.98	B	MSK	76	150	99
21-Jul-93	0.00	12.58	B	MSK	76	150	99
21-Jul-93	12.58	21.11	B	MSK	76	150	99
21-Jul-93	21.11	23.98	B	MSK	76	150	99
22-Jul-93	0.00	13.00	B	MSK	76	150	99
22-Jul-93	18.75	23.98	B	MSK	76	150	99
23-Jul-93	0.00	23.98	B	MSK	76	150	99
24-Jul-93	0.00	23.98	B	MSK	76	150	99
25-Jul-93	0.00	10.56	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
25-Jul-93	10.75	23.98	B	MSK	76	150	99
26-Jul-93	0.00	23.98	B	MSK	76	150	99
27-Jul-93	0.00	13.00	B	MSK	76	150	99
27-Jul-93	18.76	23.98	B	MSK	76	150	99
28-Jul-93	0.00	7.23	B	MSK	76	150	99
28-Jul-93	7.23	7.27	NS	MSK	76	150	
28-Jul-93	7.27	7.45	B	MSK	76	150	99
28-Jul-93	7.52	7.57	B	MSK	76	150	99
28-Jul-93	7.57	7.63	EW	MSK	76	150	
28-Jul-93	7.63	8.67	B	MSK	76	150	99
28-Jul-93	8.75	12.80	B	MSK	76	150	99
28-Jul-93	12.80	21.03	B	MSK	76	150	99
28-Jul-93	21.03	23.98	B	MSK	76	150	99
29-Jul-93	0.00	13.00	B	MSK	76	150	99
29-Jul-93	18.78	23.98	B	MSK	76	150	99
30-Jul-93	0.00	23.98	B	MSK	76	150	99
31-Jul-93	0.00	13.66	B	MSK	76	150	99
31-Jul-93	13.83	23.98	B	MSK	76	150	99
01-Aug-93	0.00	3.20	B	MSK	76	150	99
01-Aug-93	3.20	23.98	B	MSK	76	150	99
02-Aug-93	0.00	13.08	B	MSK	76	150	99
02-Aug-93	13.35	23.98	B	MSK	76	150	99
03-Aug-93	0.00	13.00	B	MSK	76	150	99
03-Aug-93	18.83	23.98	B	MSK	76	150	99
04-Aug-93	0.00	5.52	B	MSK	76	150	99
04-Aug-93	5.52	21.00	B	MSK	76	150	99
04-Aug-93	21.00	23.98	B	MSK	76	150	99
05-Aug-93	0.00	13.00	B	MSK	76	150	99
05-Aug-93	18.85	23.30	B	MSK	76	150	99
05-Aug-93	23.30	23.33	EW	MSK	76	150	
05-Aug-93	23.33	23.98	B	MSK	76	150	99
06-Aug-93	0.00	0.07	B	MSK	76	150	99
06-Aug-93	0.07	23.98	B	MSK	76	150	99
07-Aug-93	0.00	23.98	B	MSK	76	150	99
08-Aug-93	0.00	23.98	B	MSK	76	150	99
09-Aug-93	0.00	18.75	B	MSK	76	150	99
09-Aug-93	18.78	23.98	B	MSK	76	150	99
10-Aug-93	0.00	12.66	B	MSK	76	150	99
10-Aug-93	12.66	13.00	B	MSK	76	150	99
10-Aug-93	18.93	19.13	B	MSK	76	150	99
10-Aug-93	19.13	23.98	B	MSK	76	150	99
11-Aug-93	0.00	14.93	B	MSK	76	150	99
11-Aug-93	14.95	23.98	B	MSK	76	150	99
12-Aug-93	0.00	13.00	B	MSK	76	150	99
12-Aug-93	13.01	23.98	B	MSK	76	150	99
13-Aug-93	0.00	23.98	B	MSK	76	150	99
14-Aug-93	0.00	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
15-Aug-93	0.00	23.98	B	MSK	76	150	99
16-Aug-93	0.00	21.86	B	MSK	76	150	99
16-Aug-93	21.86	21.91	B	MSK	76	150	99
16-Aug-93	21.91	22.96	B	MSK	76	150	99
16-Aug-93	23.01	23.98	B	MSK	76	150	99
17-Aug-93	0.00	13.00	B	MSK	76	150	99
17-Aug-93	18.75	21.03	B	MSK	76	150	99
17-Aug-93	21.03	23.98	B	MSK	76	150	99
18-Aug-93	0.00	23.98	B	MSK	76	150	99
19-Aug-93	0.00	13.00	B	MSK	76	150	99
19-Aug-93	18.75	19.46	B	MSK	76	150	99
19-Aug-93	19.46	23.98	B	MSK	76	150	99
20-Aug-93	0.00	2.68	B	MSK	76	150	99
20-Aug-93	2.68	3.58	B	MSK	76	150	99
20-Aug-93	3.58	23.98	B	MSK	76	150	99
21-Aug-93	0.00	23.98	B	MSK	76	150	99
22-Aug-93	0.00	23.98	B	MSK	76	150	99
23-Aug-93	0.00	23.91	B	MSK	76	150	99
23-Aug-93	23.91	23.98	B	MSK	76	150	99
24-Aug-93	0.00	3.03	B	MSK	76	150	99
24-Aug-93	3.03	12.75	B	MSK	76	150	99
24-Aug-93	12.75	13.00	B	MSK	76	150	99
24-Aug-93	18.76	18.95	B	MSK	76	150	99
24-Aug-93	18.95	23.98	B	MSK	76	150	99
25-Aug-93	0.00	23.98	B	MSK	76	150	99
26-Aug-93	0.00	12.98	B	MSK	76	150	99
26-Aug-93	12.98	13.00	B	MSK	76	150	99
26-Aug-93	18.66	19.25	B	MSK	76	150	99
26-Aug-93	19.25	20.33	B	MSK	76	150	99
26-Aug-93	20.33	23.98	B	MSK	76	150	99
27-Aug-93	0.00	3.93	B	MSK	76	150	99
27-Aug-93	3.93	6.43	B	MSK	76	150	99
27-Aug-93	6.43	10.90	B	MSK	76	150	99
27-Aug-93	10.90	10.95	EW	MSK	76	150	
27-Aug-93	10.95	10.96	B	MSK	76	150	99
27-Aug-93	10.96	10.98	NS	MSK	76	150	
27-Aug-93	10.98	11.05	EW	MSK	76	150	
27-Aug-93	11.05	11.10	B	MSK	76	150	99
27-Aug-93	11.15	11.16	B	MSK	76	150	99
27-Aug-93	12.46	23.98	B	MSK	76	150	99
28-Aug-93	0.00	23.98	B	MSK	76	150	99
29-Aug-93	0.00	23.98	B	MSK	76	150	99
30-Aug-93	0.00	10.50	B	MSK	76	150	99
30-Aug-93	10.58	10.60	B	MSK	76	150	99
30-Aug-93	10.60	18.93	B	MSK	76	150	99
30-Aug-93	18.93	19.50	B	MSK	76	150	99
30-Aug-93	19.58	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
31-Aug-93	0.00	13.00	B	MSK	76	150	99
31-Aug-93	18.73	23.98	B	MSK	76	150	99
01-Sep-93	0.00	12.08	B	MSK	76	150	99
01-Sep-93	12.16	12.86	B	MSK	76	150	99
01-Sep-93	12.86	21.00	B	MSK	76	150	99
01-Sep-93	21.00	24.00	B	MSK	76	150	99
02-Sep-93	0.00	8.92	B	MSK	76	150	99
02-Sep-93	8.92	12.83	B	MSK	76	150	99
02-Sep-93	12.83	13.00	B	MSK	76	150	99
02-Sep-93	18.75	23.98	B	MSK	76	150	99
03-Sep-93	0.00	23.98	B	MSK	76	150	99
04-Sep-93	0.00	23.98	B	MSK	76	150	99
05-Sep-93	0.00	23.98	B	MSK	76	150	99
06-Sep-93	0.00	23.98	B	MSK	76	150	99
07-Sep-93	0.00	13.00	B	MSK	76	150	99
07-Sep-93	18.75	23.98	B	MSK	76	150	99
08-Sep-93	0.00	13.01	B	MSK	76	150	99
08-Sep-93	13.01	21.41	B	MSK	76	150	99
08-Sep-93	21.41	23.98	B	MSK	76	150	99
09-Sep-93	0.00	6.57	B	MSK	76	150	99
09-Sep-93	6.57	10.98	B	MSK	76	150	99
09-Sep-93	10.98	13.00	B	MSK	76	150	99
09-Sep-93	18.75	23.98	B	MSK	76	150	99
10-Sep-93	0.00	23.98	B	MSK	76	150	99
11-Sep-93	0.00	15.26	B	MSK	76	150	99
11-Sep-93	15.26	23.98	B	MSK	76	150	99
12-Sep-93	0.00	23.98	B	MSK	76	150	99
13-Sep-93	0.00	16.06	B	MSK	76	150	99
13-Sep-93	16.06	16.10	B	MSK	76	150	99
13-Sep-93	16.10	16.18	EW	MSK	76	150	
13-Sep-93	16.18	16.56	B	MSK	76	150	99
13-Sep-93	16.56	16.61	EW	MSK	76	150	
13-Sep-93	16.61	16.73	B	MSK	76	150	99
13-Sep-93	16.76	22.90	B	MSK	76	150	99
13-Sep-93	23.01	23.98	B	MSK	76	150	99
14-Sep-93	0.00	1.00	B	MSK	76	150	99
14-Sep-93	1.17	1.83	B	MSK	76	150	99
14-Sep-93	1.83	13.00	B	MSK	76	150	99
14-Sep-93	18.85	19.51	B	MSK	76	150	99
14-Sep-93	19.51	23.98	B	MSK	76	150	99
15-Sep-93	0.00	23.98	B	MSK	76	150	99
16-Sep-93	0.00	13.00	B	MSK	76	150	99
16-Sep-93	18.83	19.15	B	MSK	76	150	99
16-Sep-93	19.15	23.98	B	MSK	76	150	99
17-Sep-93	0.00	23.98	B	MSK	76	150	99
18-Sep-93	0.00	23.98	B	MSK	76	150	99
19-Sep-93	0.00	23.98	B	MSK	76	150	99

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
20-Sep-93	0.00	23.98	B	MSK	76	150	99
21-Sep-93	0.00	12.75	B	MSK	76	150	99
21-Sep-93	12.75	13.00	B	MSK	76	150	99
21-Sep-93	18.78	23.98	B	MSK	76	150	99
22-Sep-93	0.00	12.75	B	MSK	76	150	99
22-Sep-93	12.75	21.00	B	MSK	76	150	99
22-Sep-93	21.00	23.98	B	MSK	76	150	99
23-Sep-93	0.00	13.00	B	MSK	76	150	99
23-Sep-93	18.76	23.98	B	MSK	76	150	99
24-Sep-93	0.00	23.98	B	MSK	76	150	99
25-Sep-93	0.00	23.98	B	MSK	76	150	99
26-Sep-93	0.00	17.35	B	MSK	76	150	99
26-Sep-93	17.35	20.83	B	MSK	76	150	99
26-Sep-93	20.83	23.98	B	MSK	76	150	99
27-Sep-93	0.00	15.25	B	MSK	76	150	99
27-Sep-93	15.35	23.98	B	MSK	76	150	99
28-Sep-93	0.00	13.00	B	MSK	76	150	99
28-Sep-93	18.75	23.98	B	MSK	76	150	99
29-Sep-93	0.00	13.00	B	MSK	76	150	99
29-Sep-93	20.76	23.98	B	MSK	76	150	99
30-Sep-93	0.00	12.83	B	MSK	76	150	99
30-Sep-93	12.83	19.58	B	MSK	76	150	99
30-Sep-93	19.58	23.98	B	MSK	76	150	99
01-Oct-93	0.00	23.98	B	MSK	76	150	100
02-Oct-93	0.00	23.98	B	MSK	76	150	100
03-Oct-93	0.00	23.98	B	MSK	76	150	100
04-Oct-93	0.00	23.98	B	MSK	76	150	100
05-Oct-93	0.00	14.00	B	MSK	76	150	100
05-Oct-93	19.83	23.98	B	MSK	76	150	100
06-Oct-93	0.00	12.11	B	MSK	76	150	100
06-Oct-93	12.11	16.98	B	MSK	76	150	100
06-Oct-93	17.01	23.98	B	MSK	76	150	100
07-Oct-93	0.00	2.68	B	MSK	76	150	100
07-Oct-93	2.68	14.00	B	MSK	76	150	100
07-Oct-93	19.76	21.61	B	MSK	76	150	100
07-Oct-93	21.61	21.66	NS	MSK	76	150	
07-Oct-93	21.66	22.10	B	MSK	76	150	100
07-Oct-93	22.10	22.11	EW	MSK	76	150	
07-Oct-93	22.21	22.40	EW	MSK	76	150	
07-Oct-93	22.85	23.98	B	MSK	76	150	100
08-Oct-93	0.00	6.57	B	MSK	76	150	100
08-Oct-93	6.57	6.62	EW	MSK	76	150	
08-Oct-93	6.62	6.72	B	MSK	76	150	100
08-Oct-93	6.82	23.98	B	MSK	76	150	100
09-Oct-93	0.00	23.98	B	MSK	76	150	100
10-Oct-93	0.00	15.75	B	MSK	76	150	100
10-Oct-93	15.83	20.43	B	MSK	76	150	100

TRANSMITTER OPERATIONAL PARAMETERS
NRTF REPUBLIC, MI

DATE	TIMEON (GMT)	TIMEOFF (GMT)	ANT	MOD	FREQ (Hz)	CURRENT (Amps)	PHASE (Deg)
10-Oct-93	20.43	23.98	B	MSK	76	150	100
11-Oct-93	0.00	23.98	B	MSK	76	150	100
12-Oct-93	0.00	14.00	B	MSK	76	150	100
12-Oct-93	19.83	23.98	B	MSK	76	150	100
13-Oct-93	0.00	13.40	B	MSK	76	150	100
13-Oct-93	13.40	22.43	B	MSK	76	150	100
13-Oct-93	22.43	23.98	B	MSK	76	150	100
14-Oct-93	0.00	14.00	B	MSK	76	150	100
14-Oct-93	19.90	19.91	EW	MSK	76	150	
14-Oct-93	19.91	19.96	B	MSK	76	150	100
14-Oct-93	19.96	19.98	EW	MSK	76	150	
14-Oct-93	19.98	20.01	B	MSK	76	150	100
14-Oct-93	20.01	20.03	EW	MSK	76	150	
14-Oct-93	20.03	23.98	B	MSK	76	150	100
15-Oct-93	0.00	23.98	B	MSK	76	150	100
16-Oct-93	0.00	23.98	B	MSK	76	150	100
17-Oct-93	0.00	23.98	B	MSK	76	150	100
18-Oct-93	0.00	23.98	B	MSK	76	150	100
19-Oct-93	0.00	14.00	B	MSK	76	150	100
19-Oct-93	19.76	23.98	B	MSK	76	150	100
20-Oct-93	0.00	13.75	B	MSK	76	150	100
20-Oct-93	13.75	22.20	B	MSK	76	150	100
20-Oct-93	22.20	23.98	B	MSK	76	150	100
21-Oct-93	0.00	14.00	B	MSK	76	150	100
21-Oct-93	19.76	23.18	B	MSK	76	150	100
21-Oct-93	23.18	23.98	B	MSK	76	150	100
22-Oct-93	0.00	13.76	B	MSK	76	150	100
22-Oct-93	13.76	23.98	B	MSK	76	150	100
23-Oct-93	0.00	23.98	B	MSK	76	150	100
24-Oct-93	0.00	23.98	B	MSK	76	150	100
25-Oct-93	0.00	23.98	B	MSK	76	150	100
26-Oct-93	0.00	14.00	B	MSK	76	150	100
26-Oct-93	19.75	23.98	B	MSK	76	150	100
27-Oct-93	0.00	13.73	B	MSK	76	150	100
27-Oct-93	13.73	22.00	B	MSK	76	150	100
27-Oct-93	22.00	23.98	B	MSK	76	150	100
28-Oct-93	0.00	14.00	B	MSK	76	150	100
28-Oct-93	19.75	23.98	B	MSK	76	150	100
29-Oct-93	0.00	23.98	B	MSK	76	150	100
30-Oct-93	0.00	23.98	B	MSK	76	150	100
31-Oct-93	0.00	23.98	B	MSK	76	150	100
*** Total ***							
	5693.4	12494.6					

Appendix E

Detection Limits and ANOVA Table for Ambient Variables

Table 1. General analysis of variance and statistical design for climate.

Source of Variation	Sum of Squares	Mean Square	F-Ratio
SI	SS(S)	MS(S)	MS(S)/MS(E_1)
PL w SI (Error 1)	SS(E_1)	MS(E_1)	MS(E_1)/MS(E_2)
WK w PL w SI (Error 2)	SS(E_2)	MS(E_2)	
YR	SS(Y)	MS(Y)	MS(Y)/MS(E_3)
YR x SI	SS(YS)	MS(YS)	MS(YS)/MS(E_3)
YR x PLwSI (Error 3)	SS(E_3)	MS(E_3)	MS(E_3)/MS(E_4)
YR x WKwPLwSI (Error 4)	SS(E_4)	MS(E_4)	
ST	SS(T)	MS(T)	MS(T)/MS(E_5)
ST x SI	SS(TS)	MS(ST)	MS(ST)/MS(E_5)
ST x PLwSI (Error 5)	SS(E_5)	MS(E_5)	MS(E_5)/MS(E_6)
ST x WKwPLwSI (Error 6)	SS(E_6)	MS(E_6)	
MO	SS(M)	MS(M)	MS(M)/MS(E_7)
MO x SI	SS(MS)	MS(MS)	MS(M_5)/MS(E_7)
MO x PLwSI (Error 7)	SS(E_7)	MS(E_7)	MS(E_7)/MS(E_8)
MO x WKwPLwSI (Error 8)	SS(E_8)	MS(E_8)	
YR x MO	SS(YM)	MS(YM)	MS(YM)/MS(E_9)
YR x MO x SI	SS(YMS)	MS(YMS)	MS(YMS)/MS(E_9)
YR x MO x PLwSI (Error 9)	SS(E_9)	MS(E_9)	MS(E_9)/MS(E_{10})
YR x MO x WKwPLwSI(Error 10)	SS(E_{10})	MS(E_{10})	
YR x ST	SS(YT)	MS(YT)	MS(YT)/MS(E_{11})
YR x ST x SI	SS(YTS)	MS(YTS)	MS(YTS)/MS(E_{11})
YR x ST x SI (Error 11)	SS(E_{11})	MS(E_{11})	MS(E_{11})/MS(E_{12})
YR x ST x SI x WKwPLwSI(Error 12)	SS(E_{12})		
ST x MO	SS(TM)	MS(TM)	MS(TM)/MS(E_{13})
ST x MO x SI	SS(TMS)	MS(TMS)	MS(TMS)/MS(E_{13})
ST x MO x PLwSI (Error 13)	SS(E_{13})	MS(E_{13})	MS(E_{13})/MS(E_{14})
ST x MO x WKwPLwSI (Error 14)	SS(E_{14})	MS(E_{14})	
YR x ST x MO x SI	SS(YTMS)	MS(YTMS)	MS(YTMS)/MS(E_{15})
YR x ST x MO x PLwSI (Error 15)	SS(E_{15})	MS(E_{15})	MS(E_{15})/MS(E_{16})
YR x ST x MO x WKwPLwSI (Error 16)	SS(E_{16})	MS(E_{16})	

Site = SI, S Within=w
Stand Type = ST, T By=x
Year = YR, Y
Month = MO, M
Plot = PL

Table 2 Multiple range detection limits (DTL) and detection limits as a percent of overall mean (DTL%) for control vs. test site comparisons (1985-1993).

Control Vs. Ground

Variable	Site x Yr DTL	Site x Yr DTL%
Air Temperature (^{o}C)	0.43	3.56
Soil Temperature 5cm (^{o}C)	0.45	3.62
Soil Temperature 10cm (^{o}C)	0.56	4.65
Soil Moisture 5cm (%)	1.49	10.21
Soil Moisture 10cm (%)	1.39	9.53
Precipitation (cm)	1.03	61.40
Relative Humidity (%)	4.02	5.61

Control Vs. Antenna

	Site x Yr		Site x Stand Type x Yr	
Variable	DTL	DTL%	DTL	DTL
Air Temperature (^{o}C)	0.26	2.18	0.29	2.38
Soil Temperature 5cm (^{o}C)	0.30	2.62	0.69	5.90
Soil Temperature 10cm (^{o}C)	0.37	3.27	0.54	4.76
Soil Moisture 5cm (%)	1.10	8.65	1.43	11.21
Soil Moisture 10cm (%)	0.86	6.86	1.55	12.37
Precipitation (cm)	1.02	60.31		
Relative Humidity (%)	4.04	5.42		
PAR	2.7	58.6		
Air Temperature (30cm)	1.5	12.4		

Table 3. **General analysis of variance and statistical design for soil nutrients.**

Source of Variation	Sum of Squares	Mean Square	F-Ratio
SI	SS(S)	MS(S)	MS(S)/MS(E_1)
PL w SI (Error 1)	SS(E_1)	MS(E_1)	
YR	SS(Y)	MS(Y)	MS(Y)/MS(E_2)
YR x SI	SS(YS)	MS(YS)	MS(YS)/MS(E_2)
YR x PLwSI (Error 2)	SS(E_2)	MS(E_2)	

Site = SI, S Within=w
Year = YR, Y
Plot = PL

Appendix F

Publications Related to the Modeling Effort Tree Productivity

Int J Biometeorol (1993) 37:229–234

International Journal of Biometeorology IJB

Short communication

Effects of 76 Hz electromagnetic fields on forest ecosystems in northern Michigan: tree growth

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Received: September 15 / Accepted: September 29, 1993

Abstract. Since 1984, the possible effects of extremely low-frequency electromagnetic (EM) fields generated by a 76 Hz communication antenna on the growth and productivity of four deciduous and one coniferous species have been studied in the Upper Peninsula of Michigan. Results from two research sites are discussed here: one site near an antenna element and a control site located 50 km from the communication system. Growth models for individual tree diameters were developed for northern red oak (*Quercus rubra*), paper birch (*Betula papyrifera*), aspen (*Populus tremuloides* with a few individuals of *P. grandidentata*), and red maple (*Acer rubrum*). A growth model for individual tree height was developed for young red pine (*Pinus resinosa*). Average differences between the observed and predicted growth were calculated for each growing season and then compared between the study sites and across the study periods to evaluate changes in growth patterns which could be attributed to EM field effects. For aspen and red maple, the results showed a stimulation of diameter growth at magnetic flux density levels of 1 to 7 milliGauss; height growth of red pine was increased at about the same exposure levels. There are no clear indications of an EM field effect on total annual diameter growth for either of the other two species.

Key words: Bioelectric effects – Biomagnetic effects – Environmental monitoring – Change point analysis

Introduction

Over the past few years, the biological effects of electromagnetic (EM) fields at varying frequency levels have generated much interest. The majority of work has been done with controlled laboratory experiments studying the effects of EM fields; little work has examined the effects of EM fields on plant communities growing in natural settings. The United States Navy, Space and Naval Warfare Systems Command operates an extremely low frequency (ELF); (76 Hz) antenna system at the Naval Radio Transmitting Facility in Republic, Michigan. The antenna was constructed to communicate with submerged submarines around the world. Testing of the 90 km antenna began in 1986 and continued at intermediate levels until 1989 when the antenna became fully operational at 150 amperes. An intensive environmental monitoring program began in 1984 to determine whether ELF electromagnetic fields cause changes in forest productivity or health (Zapotosky 1992).

Tree growth is sensitive to a variety of environmental disturbances. One component of the study examines the growth and development of both a natural community of second-growth hardwood trees and a planted red pine plantation. Diameter growth was the response variable used for assessing the effects of ELF fields on the hardwood trees because cambial activity is responsive to environmental effects (Smith 1986) and diameter at breast height (dbh) is strongly correlated with total tree biomass (Crow 1978). For red pine, height growth was the primary response variable. Effects of the ELF fields on these response variables were examined between study sites each year and between pre-operational and operational years.

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Materials and methods

Antenna operation. The naval ELF communications system contains an antenna, which is primarily situated above the ground between a number of grounded terminals. The study sites comprised one near the antenna element (antenna site) and a control site located 50 km from the antenna system. The antenna began operation at 6 amperes (low power) in 1986, at 15 amperes in 1987, at 75 amperes in 1988, and at 150 amperes in 1989, 1990, and 1992. The antenna was at an unmodulated frequency of 76 Hz from 1986 until 1988, at modulated frequencies (72–80 Hz) for a portion of the time during 1988 and 1989, and at full frequency modulated operation from late 1989 to 1992. In 1991, because of repair work needed on the portion of the antenna near the

Table 1. Summary of stand conditions at the beginning of the growing seasons of 1985 and 1992

Variable	Antenna		Control	
	1985	1992	1985	1992
Hardwoods				
Basal area (m^2/ha)				
Northern red oak	6.57	8.69	20.00	22.70
Paper birch	0.86	0.96	2.92	1.32
Aspen	2.43	2.94	3.33	5.34
Red maple	7.78	9.54	0.52	0.78
Stems (n/ha)				
Northern red oak	167	156	559	542
Paper birch	25	25	127	45
Aspen	48	48	139	108
Red maple	457	464	57	67
Site index[a] (m at 50 years)				
Northern red oak		21		22
Paper birch		20		18
Aspen		21		20
Red maple		17		18
Age in 1985 (years)				
Northern red oak		45		50
Paper birch		53		52
Aspen		48		53
Red maple		40		43
Red pine				
Average height (cm)	23.92	299.50	22.73	328.68
Average height growth (cm)	6.61	51.58	8.34	43.81

[a] The site index represents mean dominant height (in m) at 50 years

antenna site, that segment was de-energized from May 8 to July 12. During this time, EM fields at lower than operational intensities at the antenna site were produced by EM coupling from another antenna element. This time frame coincides with an interval when 65–85% of the diameter growth of hardwood species occurs and 90% of the height growth of red pine occurs. The same antenna segment was again de-energized on December 23, 1991 to March 23, 1992.

Measurements of 76 Hz transverse, longitudinal, and magnetic fields were made on each study site each year (Haradem et al. 1991). Due to the complexity of the effects of site conditions on the air and earth electric fields, only the effects of exposure levels of the maximum magnetic flux density have been investigated to date. The fields are very predictable and interpolation equations have been developed to estimate maximum magnetic flux density exposure levels at any location within the study sites. These equations, together with tree locations mapped to the nearest 0.10 m (Reed et al. 1989), provide an estimated magnetic flux density exposure at the center of the base of each study tree. At full power (150 A), magnetic flux density exposures at the antenna site range from 5 to 10 milliGauss (mG) (mean, 7.97 mG) in the hardwood stand and 6 to 25 mG (mean, 11.70 mG) at the red pine plantation. At the control site, exposures were less than 0.0025 mG for all individuals in both stands.

Site description. The control site is located at 46° 10′ N, 88° 30′ W and the antenna site is at 46° 20′ N, 88° 10′ W. At the control and antenna sites both a stand of hardwoods and a red pine plantation were under observation. Both sites support or supported (prior to clearcutting and planting) second-growth northern hardwood vegetation, classified as the *Acer-Quercus-Vaccinium* habitat type (Coffman et al. 1983). The vegetation consisted primarily of red maple (*Acer rubrum*, L.) and northern red oak (*Quercus rubra*, L.) with minor components of quaking aspen (*Populus tremuloides*, Michx.), bigtooth aspen (*P. grandidentata*, Michx.), and paper birch (*Betula papyrifera*, Marsh.). A summary of the stand conditions is given in Table 1. All three sites are in the same regional ecosystem and have similar geology and climate (Iron District, Crystal Falls Subdistrict; Albert et al. 1986). The sites have short growing seasons (87 days) and are subject to the climatic influences of the Great Lakes. Although surface horizons of the soils are morphologically similar, the control site was classified as Alfic Haplorthod, sandy, mixed, frigid, and the antenna site was classified as an Entic Haplorthod, sandy, mixed, frigid (US Department of Agriculture Soil Conservation Service 1975).

Tree measurements. Since 1985, weekly diameter increments, to the nearest 0.008 cm, of four hardwood species have been measured with permanent dendrometer bands. These species include northern red oak, paper birch, aspen (both trembling and bogtooth), and red maple. For the planted red pine, weekly shoot growth has been measured to the nearest 1 mm since 1985. The height measurements were made from the meristematic tip or the tip of the new terminal bud to the center of the whorl of lateral branches beneath the bud. Red pine weekly measurements begin in mid-April and continued until mid-July when shoot elongation was completed. Weekly diameter measurements of the hardwoods began in mid-April and continued until early October when 50% of leaf fall has occurred. Each site was equipped with an automated ambient weather monitoring station. Three-hour averages or totals were calculated from hourly measurements of precipitation, air temperature, relative humidity, solar radiation, soil moisture (5 cm and 10 cm depths), and soil temperature (5 cm and 10 cm depths) throughout the growing season.

Growth models. Growth models for both the hardwood species and the planted red pine were developed using data collected prior to antenna activation. Reed et al. (1992) developed diameter growth models for all four hardwood species. The models incorporate a weekly timestep and are composed of four components: (1) annual potential growth, (2) an adjustment of annual potential growth to account for intertree competition, (3) an adjustment for site physical, chemical, and annual climatic properties, and

Table 2. Number of observations and deviation from expected growth for each species with class of exposure to magnetic flux density

Exposure level	Deviation from expected growth[a]									
	Northern red oak		Paper birch		Aspen		Red maple		Red pine	
mG	*n*	cm	*n*	cm	*n*	cm	*n*	cm	*n*	cm
<0.5	19	−0.01±0.02	3	−0.00±0.02	11	0.02±0.02	70	−0.02±0.01	117	−1.35±0.08
0.5–1.5	23	0.07±0.03	6	−0.01±0.01	11	0.06±0.02	80	−0.00±0.01	75	−1.26±0.22
1.5–2.5	40	0.07±0.02	6	−0.13±0.06	9	0.20±0.03	101	−0.05±0.01	55	−0.71±0.36
2.5–3.5	22	0.08±0.03	4	0.03±0.04	9	0.15±0.05	87	−0.04±0.01	44	−0.59±0.36
3.5–5.5	10	0.06±0.03	0	–	7	0.12±0.02	41	−0.08±0.01	68	−1.17±0.26
5.5–8.5	120	0.01±0.01	19	−0.13±0.04	27	0.01±0.02	306	0.05±0.01	36	−1.39±0.30
>8.5	27	0.07±0.02	6	0.01±0.04	18	0.01±0.03	133	0.06±0.01	44	−1.57±0.22

[a] Average observed minus predicted diameter growth for hardwoods (Reed et al. 1992) and height growth for red pine (Jones et al. 1991)

(4) seasonal growth pattern which accounts for weekly climatic factors. Jones et al. (1991) estimated weekly red pine shoot growth using a modified version of the Chapman-Richards growth function (Pienaar and Turnbull 1973). Weekly shoot growth, a function of cumulative air temperature degree days (4.4 °C basis), was modified by a component containing soil water potential. Ambient data on the sites were used with the growth models to calculate the expected growth for each species based on the physical, chemical, and climatic growing conditions for a given growing season. Deviations from the expected growth were examined to determine if they were related to the magnetic flux density exposure levels.

Results and discussion

For each tree species, differences between the observed growth and predicted growth (residuals) were calculated each year using the respective growth models. These differences were expected to increase if an additional factor was introduced which impacts tree growth. The differences were compared among study sites as well as between pre-operational and operational years. The independence of the growth model residuals for different years was examined. The differences from the expected growth for up to five successive years were not significantly correlated ($P<0.05$) with each other for any of the hardwood species examined on the study sites. For red pine there was a significant correlation ($P=0.05$) for a 2-year lag on each site, but all other correlations did not significantly differ from zero ($P=0.05$). This lack of correlation implies that there was no time-dependent structure to the residuals; thus observations from individual trees in each year can be assumed to be statistically independent of observations from other years.

Evaluation of the effects of ELF fields on individual tree growth between the pre-operational and operational years was conducted by examining the level of exposure to the magnetic flux density generated by the antenna. All observations were placed in one of seven classes based on the average exposure to magnetic flux density during that particular growing season: less than 0.5 mG, 0.5–1.5 mG, 1.5–2.5 mG, 2.5–3.5 mG, 3.5–5.5 mG, 5.5–8.5 mG, and greater than 8.5 mG. The data of Table 2 show the average residual and deviation (positive values indicate greater than expected growth and negative values indicate less than expected growth) for each species each year on the study sites. Figure 1 presents the same material graphically for red pine and aspen.

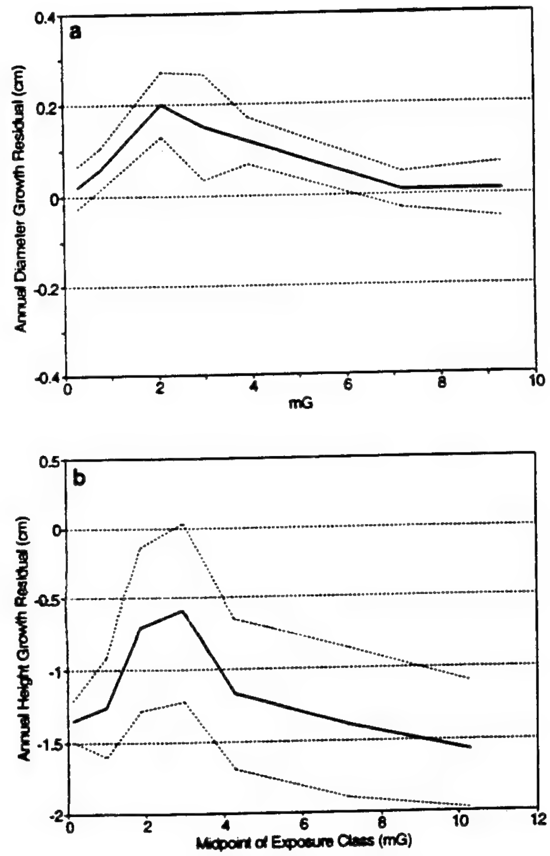

Fig. 1. The effect of electromagnetic (EM) fields on (a) aspen diameter growth residuals from the antenna site (1986–1992) and (b) red pine height growth residuals from the antenna site (1986–1992)

There was greater ($P<0.05$) than expected growth at exposure levels from 1.5 to 5.5 mG for aspen compared to growth at low (<0.5 mG) and high (>8.5 mG) magnetic flux density exposure levels. These growth differences were also greater than those at the control stands for the same time periods. For red maple, there was greater growth at high exposure levels (>8.5 mG)

than at lower levels ($P<0.05$), and after factoring out the corresponding growth for the same time periods at the control site, red maple was found to follow the same pattern as aspen, thus indicating that the greater than expected growth is due to the exposure to ELF fields. For northern red oak and paper birch, there was no pattern of growth differences from the expected values which was related to magnetic flux density exposure levels. For red pine, although the average residuals show that the predicted height growth was greater than the observed height growth, the same trend found in the aspen residuals was evident here as well. The larger residuals at exposure levels of 1.5 to 3.5 mG indicate greater than expected growth ($0.05 < P < 0.10$) compared to the growth at low (<0.5 mG) and high magnetic flux density exposure levels (>8.5 mG). This trend of greater growth was not apparent at the control site. Similar "window effects" (patterns of growth alterations at varying exposure levels) have been shown for other plants in controlled experiments as seen in Fig. 2 (Krizaj and Valencic 1989; Wiewiorka 1990; Wiewiorka and Sarosiek 1987). In each case, there was a lower threshhold of response, a stimulation of growth, and a gradually decreasing effect at higher exposure levels

To quantify the response to the electromagnetic fields, the following equation representing a modification of change point analysis (Esterby and El-Shaarawi 1981) was fitted for each species:

$$[1] R_{Aik}=\alpha_0+\beta_1\ R_{Ck}+\varepsilon_{ik},\quad \mathrm{mG}_{ik}<t_1,\ \mathrm{mG}_{ik}>t_2 \tag{1a}$$

$$[1] R_{Aik}=\alpha_0+\beta_1\ R_{Ck}+\gamma_0+\gamma_1\ \mathrm{mG}_{ik} + \gamma_2\ \mathrm{mG}_{ik}^{-1}+\varepsilon_{ik},\quad t_1\leq \mathrm{mG}_{ik}\leq t_2 \tag{1b}$$

where R_{Aik} is the residual (observed minus expected growth) from the ith tree at the antenna site in the kth year, R_{Ck} is the average residual from the same species at the control site for the kth year, mG_{ik} is the interpolated magnetic flux density exposure level for the ith tree in the kth year, and t_1 and t_2 are the lower and upper threshholds of the effect, respectively. The threshholds were constrained as follows:

$$[2]\ t_1=[-\gamma_0+(\gamma_0{}^2-4\gamma_1\gamma_2)^{1/2}]/2\gamma_1 \tag{2a}$$
$$[2]\ t_2=[-\gamma_0-(\gamma_0{}^2-4\gamma_1\gamma_2)^{1/2}]/2\gamma_1 \tag{2b}$$

For a given species, if no differences in growth exist between the antenna and control sites, then α_0 and β_1 should equal zero. A nonzero value of α_0 indicates an inherent difference in productivity for a given species between the two sites. A nonzero value of β_1 indicates that there is some environmental factor not identified in the growth models which is affecting both sites. In this case, β_1 should be approximately equal to one. If there is no response to the electromagnetic fields, after accounting for the other factors, then γ_0, γ_1, and γ_2 should all equal zero. Nonzero values of these parameters indicate an effect of the electromagnetic fields on tree growth. For aspen, red maple, and red pine, γ_0, γ_1, and γ_2 were all different from zero (Table 3), indicating an electromagnetic field effect on tree growth. The peak response occurred at 2.4, 3.2, and 2.2 mG for aspen, red maple, and red pine, respectively. The lower threshhold was about 1 mG and the upper threshhold was ca. 6–7 mG for all species. For aspen, the maximum response was 0.14 cm and for red maple 0.08 cm, increases of 48% and 74% respectively, over the average diameter growth of the trees since 1984. For comparison, these findings are of similar magnitude to the responses obtained in nutrient fertilization experiments in aspen (Van Cleve 1973).

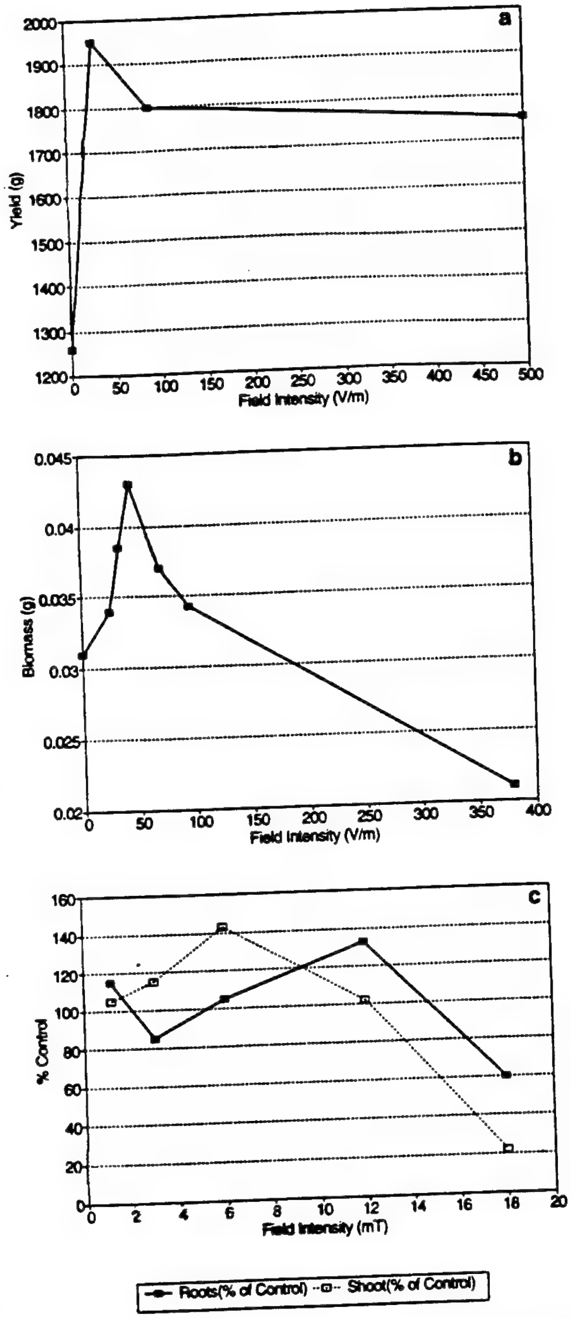

Fig. 2. The effect of EM fields on (a) tomato yields (Wiewiorka 1990), (b) liverwort biomass (Wiewiorka and Sarosiek 1987), and (c) *Lepidum sativum* (Krizaj and Valencic 1989)

Though the units used to measure exposure differ in different experiments and different plant species seem to respond to different exposure levels, the response pat-

Table 3. Estimated coefficients and their asymptotic standard errors for equations 1a and 1b for each species

Species	α_0	β_1	γ_0	γ_1	γ_2	t_1[a]	t_2[a]
Northern red oak	−0.115* (0.195)	1.058 (0.051)	0.162* (0.180)	2E-9* (0.002)	−0.009 (0.001)	–	–
Paper birch	−0.059 (0.008)	1.131 (0.063)	3.549* (2.343)	−0.635* (0.471)	−4.590* (2.901)	–	–
Aspen	0.021 (0.010)	0.178* (0.134)	0.382 (0.102)	−0.050 (0.017)	−0.290 (0.103)	0.85	6.79
Red maple	−0.032 (0.006)	1.331 (0.114)	0.469 (0.101)	−0.060 (0.014)	−0.635 (0.141)	1.73	6.08
Red pine	−0.144* (0.145)	1.107 (0.085)	1.959 (0.337)	−0.262 (0.070)	−1.208 (0.450)	0.68	6.80

[a] The asymptotic standard errors are undefined for t_1 and t_2 due to the constraints in the estimation process; the threshholds were not calculated if γ_0, γ_1, or γ_2 were not asymptotically different from zero ($\alpha=0.05$)

*The estimated coefficient is not asymptotically different from zero ($\alpha=0.05$)

terns in Figs. 1 and 2 are clearly similar. The results of controlled experiments of EM exposures may be criticized as being artifacts of the experimental procedure and the results of field studies may be criticized as being inconclusive and not able absolutely to rule out competing explanations. However when both field studies and controlled experiments indicate similar results, the causality criteria (Moesteller and Tukey 1977) of (1) the responsiveness of the experimental subjects to the treatment, and (2) the consistency of response, are satisfied. This provides strong evidence of a cause and effect relationship between the stimulus (EM fields) and the response (plant growth stimulation).

The cellular mechanisms involved in mediating this response (the third causality criterion) are unknown. A recent review article (Grundler et al. 1992) identifies three possible mechanisms of nonionizing EM field effects on cellular systems: (a) spin-mediated electromagnetic effects on chemical processes, (b) influence of weak external fields on periodic processes in a nonlinear dynamic mode, and (c) biological signal transduction and amplification. Trembling aspen, due to its extreme genetic variability, clonal method of reproduction, and the ease with which it is propogated and grown under controlled conditions, provides the ideal experimental material for investigating such effects; the results of this study provide an indication of exposure levels where such effects may be expected to occur.

A body of evidence is accumulating to suggest that at least some plants do respond to EM fields and that this response may be of the same order of magnitude as responses to other environmental perturbations, such as fertilization. It seems prudent for investigators utilizing electronic equipment, such as growth chambers or open-top chambers, in controlled experiments to at least monitor the magnitude of the EM fields generated by the experimental equipment. Similarly, field experiments which are in or near utility rights-of-way or other transmission corridors, or which utilize electronic equipment, e.g. heating or lighting of plots, may also be confounded by EM fields to an unknown degree.

Conclusion

The effects of ELF electromagnetic fields were examined by determining if the differences between the observed and expected growth values (diameter or height depending on the tree species) were related to the exposure levels of magnetic flux density. The results are consistent with a stimulation of aspen and red maple diameter growth and red pine height growth at magnetic flux density levels of 1 to 7 mG. There was no clear indication of an EM effect on diameter growth at these exposure levels for the other two hardwood species (northern red oak and paper birch). These results are similar to those obtained in controlled experiments for other plant species, though the response occurs at different exposure levels.

Acknowledgements. This publication was prepared as an account of work sponsored by the Space and Naval Warfare Systems Command (SPAWAR) of the US Navy through a subcontract (E06595-88-C-001) from the IIT Research Institute (IITRI). The results presented here reflect the individual views of the authors and are not necessarily the official points of view adopted by SPAWAR or IITRI.

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Forest Ecology and Management, 46 (1991) 201–214
Elsevier Science Publishers B.V., Amsterdam

Seasonal shoot growth of planted red pine predicted from air temperature degree days and soil water potential

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(Accepted 30 October 1990)

ABSTRACT

Jones, E.A., Reed, D.D., Cattelino, P.J. and Mroz, G.D., 1991. Seasonal shoot growth of planted red pine predicted from air temperature degree days and soil water potential. *For. Ecol. Manage.*, 46: 201–214.

On-site climatic measurements were used to model red pine (*Pinus resinosa* Ait.) shoot elongation. Three study sites each consisting of three 0.2-ha plots were cleared and planted with red pine. Shoot growth was measured weekly for 2 years. Incremental seasonal growth of the leading shoot was estimated using a difference form of a modified Chapman–Richards growth function. Weekly growth was estimated as a function of air temperature degree days (4.4°C basis), soil water potential, and total expected seasonal growth. An example using the model compares varying site and climatic conditions and their effect on the pattern of seedling height growth during the growing season as well as their effect on the total amount of height growth realized at the end of the growing season.

INTRODUCTION

The timing or pattern of growth of a species is important to forest managers when considering silvicultural treatments. Perala (1985) cited the importance of timing of shoot growth for such silvicultural treatments as insect surveys, foliar application of herbicides, and the pruning and shearing of Christmas trees. To describe the phenology of shoot elongation on red pine (Pinus resinosa Ait.), Perala (1985) found that climatic conditions were more useful predictors than calendar date. Using regional climatic information to calculate air temperature degree days, he explained much of the variation in the timing and amount of shoot elongation among sites. He speculated that much of the unexplained variation may be due to other climate-dependent factors such as soil moisture content or differences in microclimate between his red

pine measurement plots and weather stations. To refine the understanding of the relative contributions of temperature and soil moisture in describing shoot elongation, this paper focuses on a growth model that was developed using site-specific, rather than regional, measures of both air temperature and soil water potential.

METHODS

Site description

Data were taken from three young red pine plantations located in the central Upper Peninsula of Michigan. Site 1 is in Iron County (46°20′N, 88°10′W). Sites 2 and 3 are both in Marquette County (46°20′N, 88°10′W). Before clearcutting, all three sites supported primarily undisturbed second-growth northern hardwood vegetation and were classified in the *Acer–Quercus–Vaccinium* habitat type (Coffman et al., 1983). All three sites are within the same regional ecosystem, suggesting comparable climate as well as geology (Iron District, Crystal Falls Subdistrict; Albert et al., 1986). The sites are subject to the climatic influences of the Great Lakes and have a short growing season of 87 days. The soils, though morphologically similar in surface horizons, were classified differently. Site 1 is an Alfic Haplorthod, sandy, mixed, frigid; site 2 is an Entic Haplorthod, sandy, mixed, frigid; and site 3 is a Typic Dystrocept, sandy, mixed, frigid (US Dep. Agric. Soil Conservation Service, 1975). Although they are classified differently, previous studies have indicated similar overstory productivity on these soil types (Shetron, 1972).

Tree measurements

In June 1984 the study sites were cleared of existing vegetation by whole-tree harvesting. Three permanent measurement plots (46 m×46 m) were then established at each site. These areas were immediately planted (3-0 red pine seedlings from a local seed source and obtained from the USDA Forest Service Toumey Nursery in Watersmeet, MI) on a 1 m×1 m spacing. One hundred of the red pine seedlings were randomly selected from each plot and permanently marked for measurements. Weekly shoot measurements were made to the nearest 1 mm on each of the marked red pine seedlings. Measurements were made from the meristematic tip or the tip of the new terminal bud to the center of the whorl of lateral branches beneath the bud. These weekly measurements began in mid-April while shoots were still dormant and continued until mid-July when shoot elongation was completed. Only the 1986 and 1987 growing seasons are included in this study because respective climatic data for the 1985 season are unavailable. In 1986, there were 14 weeks of shoot growth measurements and in 1987 there were 18 weeks of shoot

TABLE 1

Average stand characteristics for the red pine plantations on the three sites during the 1986 and 1987 growing seasons

	Site 1	Site 2	Site 3
Average total height (cm) at beginning of 1986	28.33	23.92	22.73
Average weekly incremental shoot growth (cm) for 1986	1.81	1.23	1.17
Average weekly incremental shoot growth (cm) for 1987	1.97	1.49	1.66
Average seasonal shoot growth (cm) for 1986	23.35	17.53	16.32
Average seasonal shoot growth (cm) for 1987	35.21	26.55	29.48
Average accumulated degree days for 1986	1021.53	998.23	953.73
Average accumulated degree days for 1987	1379.63	1288.67	1262.37

growth measurements. Seasonal shoot growth averaged from 16.3 to 35.2 cm over these 2 years (Table 1).

Ambient measurements

A Handar 540A[a] ambient monitoring platform was located in a cleared area at each of the three study areas. Each ambient monitoring platform contained sensors to measure precipitation, air temperature, relative humidity, and solar radiation. The three plots within each site were equipped with thermistor resistance sensors to measure air temperature at 2 m above the ground. They were also equipped with thermistor resistance sensors for soil temperature and 0–5 V differential floating sensors for soil moisture at depths of 5 cm and 10 cm. Three-hour averages were calculated for each variable, transmitted, and recovered via the GEOS East satellite and telephone lines each night. From these data, cumulative air temperature degree days were calculated on a 4.4°C basis (40°F), which is a common temperature for shoot growth studies (Perala, 1985). This heat unit approach has been in use for some time to explain plant and temperature relationships (Wang, 1960). The calculation is as follows:

$$ATDD = (\Sigma ADT - 4.4)$$

where the summation is on a weekly basis, and ATDD is air temperature de-

[a]Brand names and trademarks are given for information purposes only; no recommendation or endorsement is intended or implied.

gree days and ADT is average daily air temperature. These daily values were summed to coincide with the weekly shoot growth measurements. Average accumulated degree day totals for each growing season at each site are found in Table 1.

Soil water potential was determined to estimate moisture stress (Richards, 1965). Although soil moisture content gives a measurement of the amount of water contained in the soil, it does not reflect the degree to which plants can utilize this water. The potential determines to a large extent the availability of water to plants. Using methodology described by Richards (1965), curves were developed that relate soil water potential to the moisture content for each plot. Soil water potential values (−MPa) were estimated using these curves and daily field soil moisture content; they were averaged over 7 days to correspond to the weekly shoot growth measurements. Average seasonal values for each site are found in Table 1.

Growth model

The amount of shoot growth expected in a given week is estimated using a difference form of a modified Chapman–Richards growth function (Pienaar and Turnbull, 1973) and the cumulative air temperature degree days at the beginning and the end of the week. Soil temperature degree days at depths of 5 and 10 cm were considered, but preliminary screening showed that air temperature degree days (on a 4.4°C basis) explained more of the variation between sites. A negative exponential component modifies the expected growth based on soil water potential (Zahner, 1968). Moisture was assumed possibly to be limiting if soil water potential levels were above 0.101−MPa (1 atm). Above this point there is no free water in the soil. Soil water potential was estimated at depths of 5 and 10 cm based on soil moisture content measurements at these depths. The model incorporating soil water potential at the 10 cm depth explained more of the variation (higher R^2 and lower mean square error) in height growth than the model incorporating soil water potential at the 5 cm depth.

The model performs dynamically through the differential accumulations of air temperature degree days and is modified by soil water potential. The form of the model is as follows:

$$g_t=\{[1-\exp(-b_1AT_{2t})]^{b_2}-[1-\exp(-b_1AT_{1t})]^{b_2}\}$$
$$(G)\{\exp[b_3(M_t-0.101)]\} \qquad (1)$$

where g_t is the amount of shoot growth (0.1 cm) occurring in week t, G is the expected total shoot growth (0.1 cm) in the growing season (this may be estimated from site index curves), AT_{1t} is the cumulative air temperature degree days (4.4°C) to the beginning of week t, AT_{2t} is the cumulative air tem-

perature degree days (4.4°C) to the end of week t, M_t is the average soil water potential for week t (if actual soil water potential is less than 0.101 – MPa, M was set to 0.101 – MPa for model development), b_1 and b_2 are estimated coefficients for the air temperature degree days component, and b_3 is the estimated coefficient for the moisture stress component.

Data were fitted by nonlinear regression using the SAS subroutine NLIN (SAS Institute, 1985) to a full model containing the moisture stress component as well as a reduced model composed only of accumulated air temperature degree days. This procedure was carried out for each growing season on each site. Significant differences ($P<0.05$) were assumed between sites or years if asymptotic 95% confidence intervals for respective coefficients did not overlap.

RESULTS AND DISCUSSION

The reduced growth model containing only the air temperature degree days component was fitted to data from each site during each study year. Significant differences ($P<0.05$) between study years were found for estimates of b_2 for each of the three study sites. To account for these yearly differences, the data were then fitted to the full growth model containing the soil water potential component. On sites 2 and 3 in 1987, however, average soil water potential never exceeded 0.101 – MPa. For this reason, the model was not fitted to data from these two sites during that year. Results from these analyses indicate significant differences ($P<0.05$) among sites and years for both b_2 and b_3. Estimates of b_3, the coefficient of the soil water potential component, were significantly different from zero in all cases, indicating its usefulness in the overall growth model.

Red pine has deterministic growth, thus the amount of growth in a given growing season is in part determined by the size of the terminal bud which is formed during the preceding year (Olofinboba and Kozlowski, 1973). The high R^2 (0.89) showed that shoot growth is not solely dependent on bud size and that the current year's weather is also very important.

Perala (1985) contended that the duration of shoot growth varies with amount of total seasonal growth. Thus, as total shoot growth increases, the duration of growth also increases. This concept affects the interpretation of the coefficients b_1 and b_2 in the growth model and could account for the site and year differences found in the b_2 estimates. These two coefficients were rewritten as follows:

$$b_i = b_{i1} G^{b_{i2}} \tag{2}$$

where b_i may either be b_1 or b_2. The parameters b_{i1} and b_{i2} are now used to estimate b_1 or b_2. The effect of seasonal shoot growth on the coefficient b_2 was

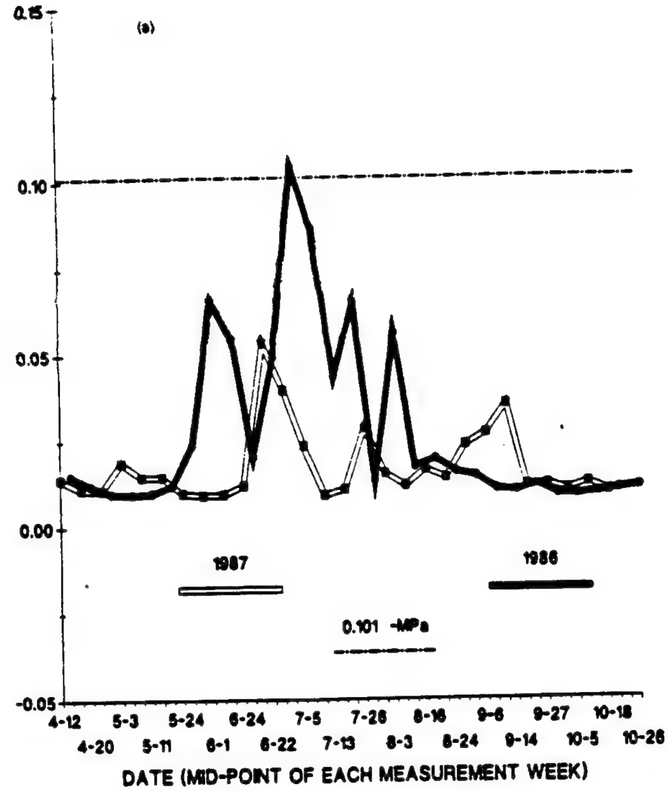

Fig. 1. Soil water potential ($-$MPa) at 10 cm for (a) site 1, (b) site 2, and (c) site 3.

found to be highly significant, but not on the coefficient b_1. Using these results, the model form was rewritten as follows:

$$g_t=\{[1-\exp(-b_1AT_{2t})]^{b_{21}Gb_{22}}-[1-\exp(-b_1AT_{1t})]^{b_{21}Gb_{22}}\}$$
$$(G)\{\exp[b_3(M_t-0.101)]\} \qquad (3)$$

where b_2 has been redefined as $b_2=b_{21}G^{b_{22}}$ and all other variables are as previously defined. Fitting this new model to data for each site within each study year eliminated yearly differences in the coefficient estimates at each site.

With yearly differences accounted for, study years were combined and coefficient estimates for each study site were examined. Estimates of b_3, the coefficient associated with soil water potential were significantly different from zero ($P<0.05$) for sites 1 and 3. At site 2 this was not the case. Low soil moisture is a relatively infrequent occurrence at the study sites except possibly during the month of July (Albert et al., 1986). During the 1987 red pine

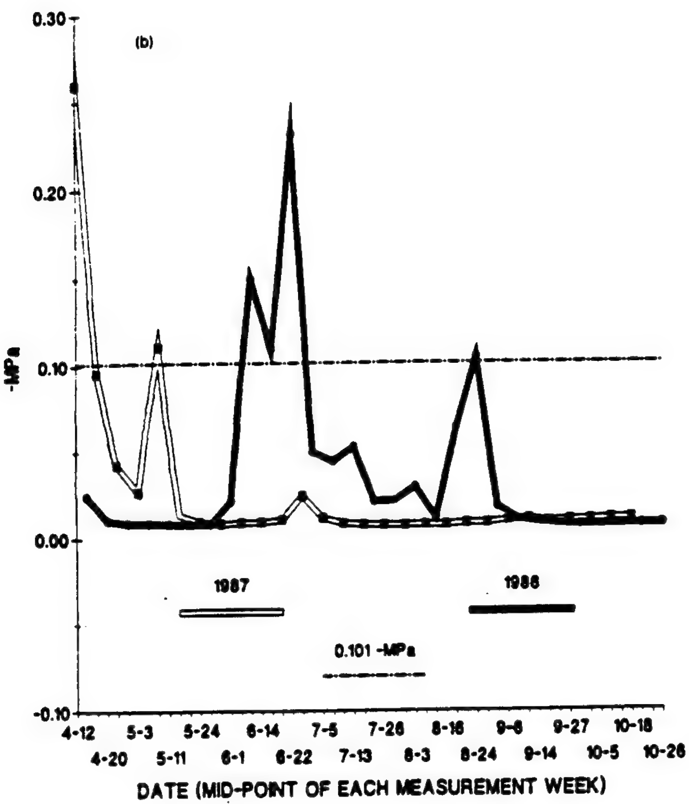

Fig. 1. Continued.

growing season, average weekly soil water potential never exceeded 0.101 – MPa at either site 2 or site 3; site 1 had several weeks where average soil water potential was above 0.101 – MPa (Figs. 1 (a), (b), and (c). In 1987, site 2 again had adequate soil moisture (1 week had an average above 0.101 – MPa). This fact could account for the coefficient not being significantly different from zero ($P<0.05$) at this site. The significance of b_3 at the other two sites indicates the importance of this component to the overall model.

When study years were combined, there was one significant difference ($P<0.05$) in the coefficient estimates among sites. The estimate of b_{22} at site 1 was slightly different (asymptotic 95% confidence intervals do not overlap, but 99% confidence intervals do) from the respective estimates at sites 2 and 3. Nevertheless, based on these results, we concluded that there was sufficient justification for combining the study sites for a single set of coefficient estimates (Table 2) for the final growth model (Eqn. (3)). Predicted and ob-

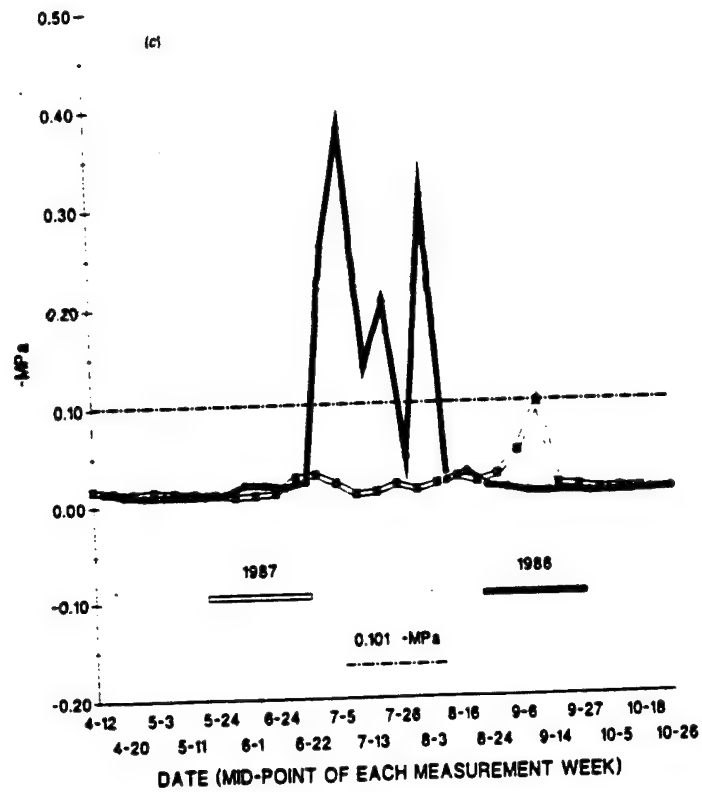

Fig. 1. Continued.

TABLE 2

Summary statistics for the final model with sites and study years combined

	Coefficient estimate	Asymptotic 95% confidence interval
b_1	0.0069	(0.0068, 0.0070)
b_{21}	1.7595	(1.5262, 1.9928)
b_{22}	0.4024	(0.3633, 0.4413)
b_3	−1.7601	(−2.1119, −1.4083)

% variation explained: 88.6%

served average shoot growth are given for each of the three sites in Figs. 2(a)–(c). The differences in observed vs. predicted shoot growth early in the growing season can be attributed to bud swell before elongation. By the middle of

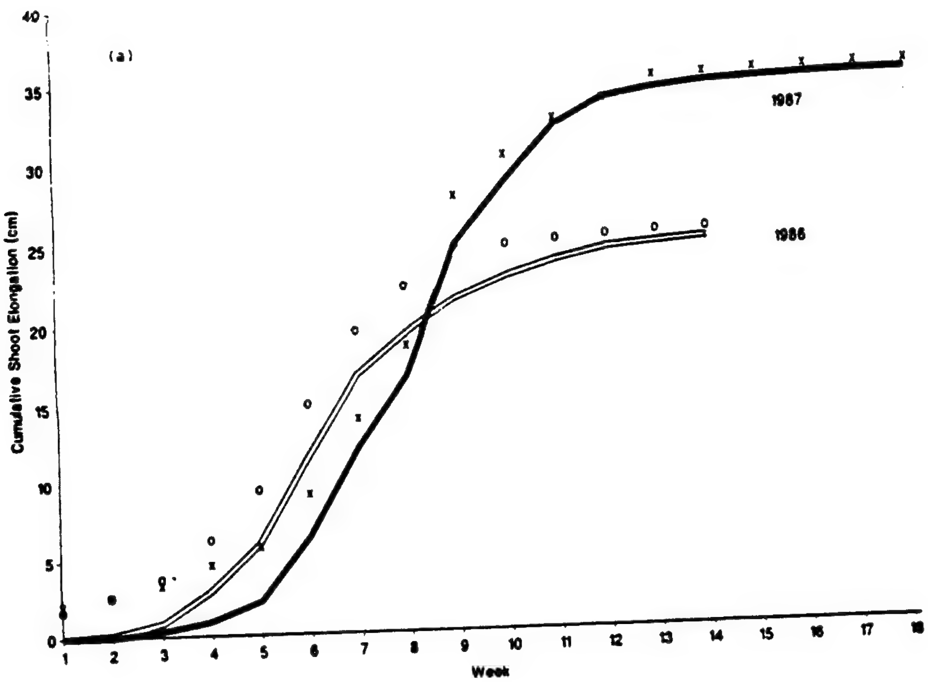

Fig. 2. Predicted and observed average red pine shoot growth (cm) for (a) site 1, (b) site 2, and (c) site 3, where observed average shoot growths are denoted by single points and predicted average shoot growth are denoted by lines.

the growing season, especially in 1987, few differences exist between the observed and predicted averages.

Predicted height growth

Using this model, a series of site and weather conditions were used to simulate and compare the predicted pattern of seedling height growth during the growing season as well as the total amount of seedling height growth realized at the end of the season. Eight comparisons were made utilizing the range of conditions observed on the study sites. A high-quality site (simulated by setting potential growth to be 30 cm) and a low-quality site (simulated by setting potential growth to be 15 cm) were compared under the following conditions:

(1) hot growing season (1400 degree days accumulated by the end of the growing season);

(2) cold growing season (900 degree days accumulated by the end of the growing season);

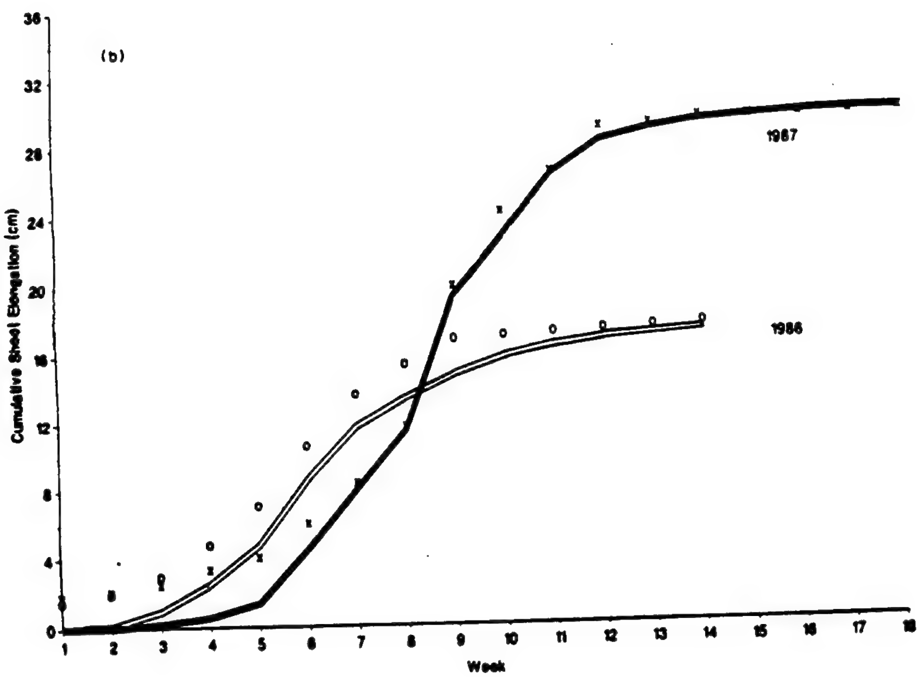

Fig. 2. Continued.

(3) wet growing season (soil water potential 0.101 – MPA or lower);

(4) dry growing season (soil water potential of 0.55 – MPA for the weeks in June and July, 0.101 – MPA or less for all other weeks).

The pattern or timing of height growth was similar for both high- and low-quality sites. Height growth started and ended earlier during a hot growing season than during a cold growing season. There was generally a 2–3 week lag in the timing of height growth during a cold vs. a hot growing season, where height growth started and ended sooner during a hot year. At either site during a hot growing season, height growth during a dry year generally ended half a week earlier than during a wet year (Table 3). The greatest amount of height growth was achieved on the high-quality site, regardless of the climatic conditions. There was little difference in the total height growth at either site during a wet growing season. The greatest reduction in total height growth occurred when the growing season was both cold and dry (Table 3), when height growth was reduced by up to 50%. Figures 3(a) and (b) depict the height growth pattern for each of the simulated weather conditions on the two sites.

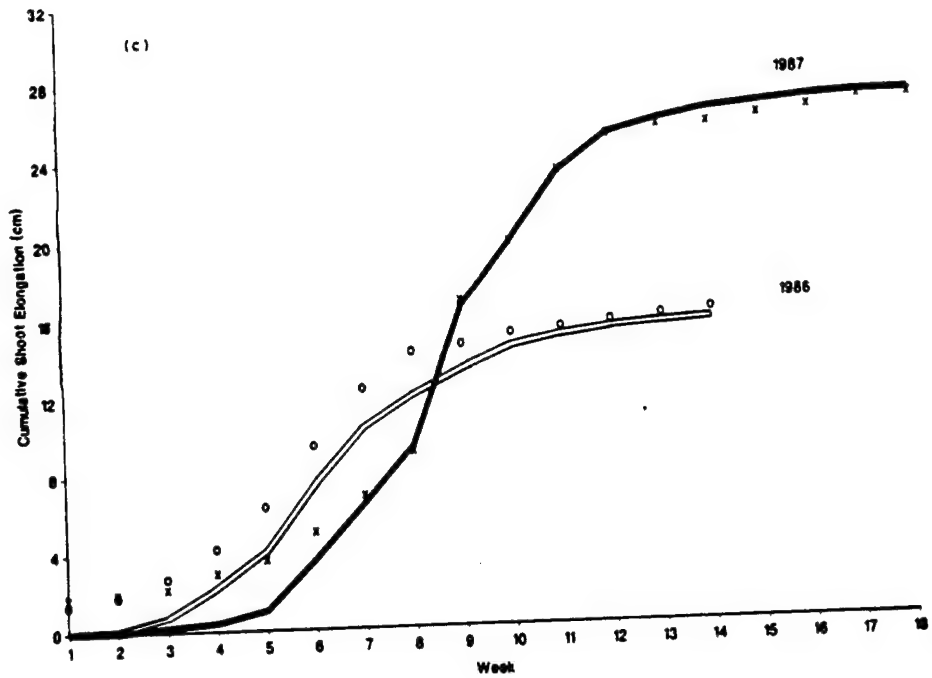

Fig. 2. Continued.

TABLE 3

Results from simulations using the shoot growth model with varying temperature and moisture regimes at the high- and low-quality sites[a]

	No. of weeks to achieve approximately		Total amount of growth (cm)
	50% growth	90% growth	
High-quality site			
Hot, wet[b]	7	10	29.99
Hot, dry[b]	6–7	9	21.16
Cold, wet[b]	10	14	29.64
Cold, dry[b]	10	14	15.84
Poor-quality site			
Hot, wet	7	10	14.99
Hot, dry	6–7	9	11.36
Cold, wet	9	13	14.86
Cold, dry	9	13	8.57

[a]A high-quality site has a potential growth (G) of 30 cm and a low-quality site has a G of 15 cm.
[b]The temperature regimes simulated include hot (1400 degree days accumulated) and cold (900 degree days accumulated) and the moisture regimes simulated include wet (soil water potential 0.101 – MPA or less) and dry (soil water potential 0.55 – MPa for weeks in June and July, 0.101 – MPa or less for all other weeks).

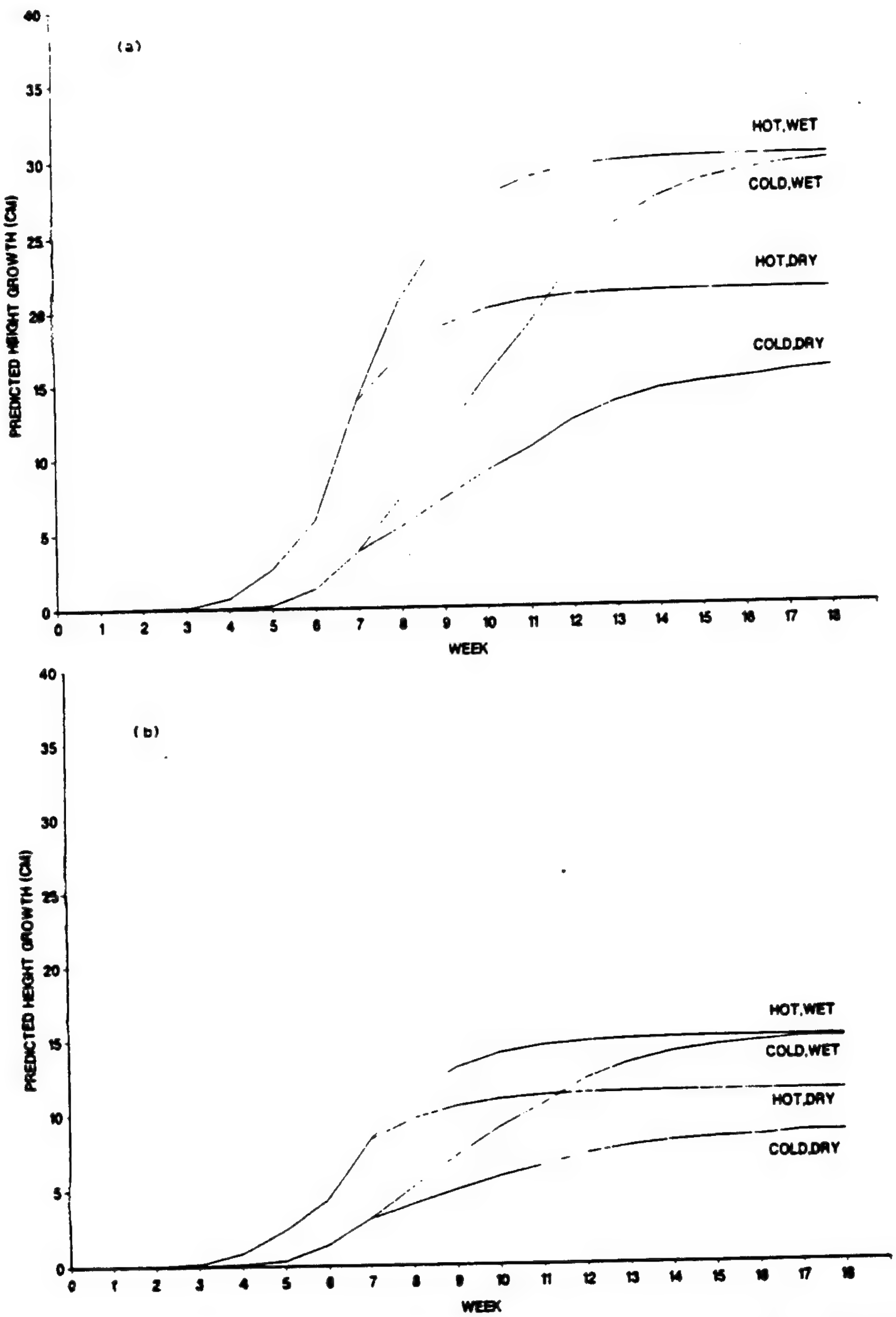

Fig. 3. Predicted shoot growth on (a) high-quality site (potential growth of 30 cm) and (b) low-quality site (potential growth of 15 cm) for simulated combinations of temperature (1400 (hot) vs. 900 (cold) total degree day accumulations) and moisture (soil water potential 0.101 – MPa or less (wet) for all weeks vs. soil water potential of 0.55 – MPa (dry) for weeks in June and July and 0.101 – MPa or less all other weeks).

SUMMARY AND CONCLUSIONS

Earlier work by Perala (1985) used air temperature degree days to predict red pine shoot growth with data collected from local weather stations. This study used site-specific data, with similar results. Cumulative air temperature degree days was the dominant factor in predicting the amount of shoot growth of red pine at any point in time during the growing season. However, differences among study sites and between study years were found. By redefining one coefficient in terms of total seasonal growth to account for the relationship of duration of shoot growth to total seasonal growth and by adding soil water potential to the model, these differences were eliminated. This allowed the development of a single set of coefficient estimates for a red pine shoot growth model (Eqn. (3)).

An example comparing various site and weather conditions and their effect on the pattern and the amount of seedling height growth during the growing season found that high-quality sites yielded the greater amounts of total growth regardless of the weather conditions, and for any site, a hot and wet growing season yielded the greatest amount of total height growth. The timing or pattern of growth during the growing season was affected by varying weather conditions. For any given site, during a hot, dry year, growth ends earlier than with any other set of conditions. During a cold year, growth ends later than during warm years. This example provides a general illustration of the model predictions; with this model a manager has a means of determining when and how much shoot growth occurs during the growing season, thus allowing for improved management planning.

ACKNOWLEDGMENTS

This study was funded by a grant from the US Navy Space and Naval Warfare Systems Command through a subcontract to the Illinois Institute of Technology Research Institute under contract E06595-88-C-001.

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Forest Ecology and Management, 54 (1992) 95–114
Elsevier Science Publishers B.V., Amsterdam

Modeling diameter growth in local populations: a case study involving four North American deciduous species

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(Accepted 25 November 1991)

ABSTRACT

Reed, D.D., Jones, E.A., Holmes, M.J. and Fuller, L.G., 1992. Modeling diameter growth in local populations: a case study involving four North American deciduous species. *For. Ecol. Manage.*, 54: 95–114.

Many existing models representing the growth of forest overstory species as a function of environmental conditions make a number of assumptions which are inappropriate when applied to local populations. For example, maximum tree diameter and height are often assumed to be constant limiting factors for a given species even though growth functions can often be localized by utilizing information in the forest growth and yield literature to make site-specific estimates of these values. Most existing models also use an annual timestep which may be inappropriate when attempting to model the growth response of individual trees to environmental conditions. In this study, a model utilizing a weekly timestep is described and applied to four widespread North American deciduous tree species. Because response to environmental conditions can vary regionally as a result of genetic heterogeneity, the resulting model should not be considered as universally appropriate for these species. This study illustrates methods which can be utilized to develop models for application to local populations.

A number of recent studies have utilized information from forest growth models and existing forest monitoring data to investigate the effects of environmental stresses on forest productivity. Examples include the work by Holdaway (1987) investigating the regional effects of acidic deposition on forests in the northcentral USA, and work by Botkin et al. (1989) projecting the

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possible effects of climate change on the forests of Michigan. These and similar studies utilize growth models to study the effects of an imposed environmental factor against a background of natural variability in climate and other factors.

There are a number of existing models which attempt to describe annual diameter growth as a function of tree and stand characteristics while accounting for the effect of site physical, chemical, and climatic properties. Diameter growth functions of the JABOWA (Botkin et al., 1972) and FORET (Shugart and West, 1977) models and models of the type described by Reed (1980) and Shugart (1984) are examples. There have been a number of models developed recently but many of these utilize the growth functions based on the methods presented in these earlier papers. In any case, most models are based on certain species-specific characteristics (such as maximum observed diameter and height) and observations relating site physical, chemical, and climatic conditions to species productivity (such as the climatic conditions at the limits of the species' geographic range).

Productivity here is defined as annual aboveground overstory biomass accumulation. While monitoring of actual biomass production over time is not feasible in field situations, it is relatively easy to accurately and precisely measure cambial development. There is a strong relationship between a tree's diameter at breast height and total tree biomass (Crow, 1978). Furthermore, cambial activity is strongly related to climatic variation, competition from neighboring trees, and site physical and chemical properties (Spurr and Barnes, 1980; Smith, 1986). For these reasons, diameter increment was chosen as the response variable representing biomass increment.

The diameter growth functions of the JABOWA and FORET models were tested by Fuller et al. (1987) on the two study sites described below and found to perform poorly when compared to actual field measurements. For all species on the sites, the models proved to be poorer predictors of individual tree diameter increment than simply using the mean diameter growth of the stands. Desanker and Reed (1993) extended these comparisons over a total of seven growing seasons and also included the growth functions from the STEMS (Belcher et al., 1982) and FOREST (Ek and Monserud, 1974) growth models. Average differences of at least 200% between observed and predicted diameter increments were observed for each of the models for at least 1 year, with some differences as high as 3000%. Clearly, such errors are unacceptable when attempting to evaluate the effects of forest stress factors which may impact growth by less than 100%. Desanker and Reed (1993) conclude that forest growth models can not simply be taken off the shelf and applied to any site (even within the geographic range of the models) without somehow adjusting for local site conditions.

There are several reasons for the inaccuracy of the predictions made by these models. An annual timestep may not be adequate when attempting to

quantify the effects of environmental stress on forest productivity. Charles-Edwards et al. (1986) indicate that the amount of time for individual plant growth processes to stabilize following a pertubation in the nutrient status of the rooting environment is on the order of 10^5 s (a few days) and the recovery time of a natural system on the order of 10^9 s (many years). It is illogical to use a timestep which is longer than the recovery time of the system of interest, whether that system is an individual plant or plant community. It is also counterproductive to use a timestep that is many orders of magnitude less than the recovery time of the system of interest. Since the interest here involves individual plants and their response to competition from neighboring plants as well as environmental factors, an intermediate timestep of 1 week was utilized in developing a diameter growth model of the type described by Reed (1980).

Models of the type described above may also perform poorly on specific sites because the species attributes they utilize are not applicable across the entire geographic range of a species. The maximum expected diameter and height for a species is dependent on genotype and site conditions and is not constant over the entire range of the species. There is a great amount of information in the forest growth and yield literature relating tree growth and development to site quality class or site index which can be utilized to make forest growth models more site specific.

A diameter growth model using site-specific species attributes and observed relationships between diameter growth, competition, and site physical, chemical, and climatic properties is presented below for two study sites in Upper Michigan. The purpose is to develop a model which can be used to estimate the effects of an imposed environmental factor against a background of natural environmental variability in a local population. The relationships given here reflect the genotypes and environmental conditions on the study sites and can not be expected to extend over the entire geographic ranges of these species. The methodology for identifying and quantifying these relationships is applicable to other study sites and species.

METHODS

Site description

The two study sites are located in the central Upper Peninsula of Michigan. Site 1 is at 46°10′N, 88°30′W and Site 2 is at 46°20′N, 88°10′W. Both sites have relatively undisturbed second growth deciduous vegetation consisting principally of red maple (*Acer rubrum*, L.) and northern red oak (*Quercus rubra*, L.) with minor components of quaking aspen (*Populus tremuloides*, Michx.), bigtooth aspen (*Populus grandidentata*, Michx.), and paper birch (*Betula papyrifera*, Marsh.). The sites are both characterized as the *Acer-*

Quercus-Vaccinium habitat type (Coffman et al., 1983). The soil at Site 1 is classified as an alfic haplorthod, sandy, mixed, frigid; the soil at Site 2 is classified as an entic haplorthod, sandy, mixed, frigid (USDA Soil Conservation Service, 1975). Past studies have documented similar northern deciduous forest productivity on these two soil types (Shetron, 1972). Both sites are within the same regional ecosystem (Iron District, Crystal Falls Subdistrict (Albert et al., 1986). The study sites are typical of forests on well-drained sandy soils of the region.

Field measurements

Measurement of radial increment was accomplished using a band dendrometer as described by Cattelino et al. (1986). The dendrometer bands were read weekly to the nearest 0.008 cm of diameter. Dendrometer bands of this type have the ability to measure diurnal shrinking and swelling of the tree bole which introduces some variability into the measurements. By standardizing the day of the week and approximate time of day to make measurements, and by following individual trees over a number of years, the negative effects of this measurement variability are minimized while the positive effects of being able to detect growth pattern across the season are maximized. Readings began in early April and continued through the growing season until over 50% of leaf fall had taken place. There were 274 trees banded on Site 1 and 197 trees banded on Site 2 prior to the 1985 growing season. Weekly measurements were made over the 1985, 1986, 1987, and 1988 growing seasons. Locations of the individual trees were mapped on a Cartesian coordinate system with a 0.1 m resolution (Reed et al., 1989). Stand conditions at the beginning of the modeling efforts (1986) are given in Table 1.

The second category of field measurements include climate and soil properties which may affect plant growth processes. Each study site was equipped with a remote data collection platform located in a cleared area adjacent to the site. The main data collection platform contained sensors measuring precipitation, air temperature, relative humidity, and solar radiation; each of three 30 m$\times$35 m plots at each site contained sensors measuring air temperature, soil temperature, and soil moisture content at 5 and 10 cm depths. Sensors were queried every 30 min and computed into 3 h mean values by the platform microprocessor. Precipitation data are logged once every 3 h. Data were retrieved eight times daily via NOAA satellite transmissions. These daily climatologic and soil data were then summarized into weekly averages to coincide with the dendrometer band readings for analysis. Physical descriptions of each pedogenic soil horizon were made at the beginning of the study. The upper 15 cm of mineral soil were sampled monthly during the growing season for determination of nutrient levels.

TABLE 1

Stand characteristics at the beginning of the study (1986)

Species	Average diameter (cm)	Average height (m)	Average basal area (m^2 ha^{-1})	Density (stems ha^{-1})	Site index (m @ 50 years)	Age (years)
Site 1						
Northern red oak	20.82	22.24	20.00	556	22	52
Paper birch	16.30	20.63	2.92	127	18	54
Aspen	22.82	23.51	3.33	79	20	55
Red maple	11.85	16.31	0.52	48	18	45
Site 2						
Northern red oak	22.69	17.62	6.57	143	21	47
Paper birch	20.42	19.62	0.86	25	20	55
Aspen	25.37	20.27	2.43	48	21	50
Red maple	15.23	16.43	7.78	410	17	42

GROWTH MODEL FORMULATION

The basic growth model formulation follows the conceptual model described by Botkin et al. (1972) and Reed (1980). In the model, the diameter growth during a given week, d_t, is represented as a function of tree, stand, climate, and site physical and chemical factors. These factors are incorporated in four model components: (1) annual potential growth (PG); (2) the adjustment of annual potential growth to account for intertree competition (IC); (3) the adjustment of annual potential growth to account for site physical, chemical, and annual climatic properties (SPC); (4) the seasonal growth pattern and further adjustment of annual potential growth to account for weekly climatic factors (SGP_t).

Each of the last three components is expressed as a proportion of the annual potential growth and the weekly diameter growth is expressed as the product of the four components

$$d_t = PG \times IC \times SPC \times SGP_t \quad (1)$$

Annual potential growth

In the above formulation, annual potential growth is defined as the amount of diameter growth that a tree could achieve if no environmental variables limit growth. Fuller (1986) identified the model form given by Botkin et al. (1972) for use on these study sites. A slightly modified form of this model is used to represent potential growth (PG) on the study sites

TABLE 2

Coefficient estimates (and associated asymptotic 95% confidence limits for statistically estimated coefficients) for the four species

	Species			
	Northern red oak	Paper birch	Aspen	Red maple
Annual potential diameter growth component				
Site index (m @ 50 years)				
Site 1	22.0	19.8	18.3	17.7
Site 2	20.7	20.7	20.1	17.1
H_{max} (cm)				
Site 1	2416	2278	2204	2105
Site 2	2359	2324	2287	2077
D_{max} (cm)				
Site 1	73	60	60	52
Site 2	72	61	60	51
b_2				
Site 1	62.438	71.367	68.900	75.692
Site 2	61.722	71.705	71.667	76.078
b_3				
Site 1	0.42766	0.59472	0.57417	0.72781
Site 2	0.42863	0.58775	0.59722	0.74587
G	200.78 (174.45, 227.10)	139.23 (69.25, 209.22)	112.92 (98.08, 127.76)	133.47 (117.63, 149.31)

Intertree competition component				
a	0.0557	0.0431	0.1206	0.0352
	(0.0443, 0.0671)	(0.0150, 0.0712)	(0.0919, 0.1493)	(0.0290, 0.0414)
Site physical, chemical and climatic factor component				
c_0	−3.32	0	−47.28	−40.35
	(−12.75, 6.31)		(−59.55, −35.02)	(−33.93, −46.77)
c_1	−0.0045	−0.0025	0.0356	0.0890
	(−0.0056, 0.0034)	(−0.0044, −0.0007)	(−0.0429, −0.0283)	(0.0696, 0.1084)
c_2	0.1081	0	0.3456	0.1498
	(−0.0514, 0.2671)		(0.1429, 0.5503)	(0.0695, 0.2302)
c_3	0	−37.26	0	12.71
		(−56.11, −18.42)		(6.47, 18.95)
Seasonal growth pattern component				
d_1	809.67	725.75	713.97	761.11
	(762.75, 856.60)	(586.83, 765.68)	(693.07, 734.87)	(740.06, 782.16)
d_2	1.4351	2.1470	2.2878	2.1322
	(1.3595, 1.5107)	(2.1132, 2.7207)	(2.1597, 2.4159)	(2.0256, 2.2388)
d_3	−0.5125	−0.3278	0	−0.5005
	(−0.7882, −0.2367)	(−0.5708, −0.0849)		(−0.7133, −0.2876)

$$\mathrm{PG}=\frac{GD(1-D/D_{\max})}{274+3b_2D-4b_3D^2} \tag{2}$$

where D is tree diameter at breast height (DBH; cm), $D_{\max}$ is the maximum observed tree diameter for a species (cm), and G, b_2, and b_3 are species-specific constants. Botkin et al. (1972) included height and the species' maximum height (both in centimeters) in their model formulation; because of the difficulty in precisely measuring height and annual height growth in mature deciduous individuals, these variables were not directly included in the model formulation in this study. To insure logical predictions are obtained when D is near $D_{\max}$ (to insure that PG=0 when $D=D_{\max}$ and $H=H_{\max}$), Botkin et al. (1972) imposed the following constraints on b_2 and b_3

$$b_2=2(H_{\max}-137)/D_{\max} \tag{3}$$

$$b_3=(H_{\max}-137)/D_{\max^2} \tag{4}$$

These constraints were imposed on b_2 and b_3 in this study as well to retain the logical behavior of PG.

Fuller (1986) and Desanker and Reed (1993) found that the model with the values of the coefficients given by Botkin et al. (1972) performed poorly on the study sites and required re-estimation. As discussed by Botkin et al. (1972), Reed et al. (1990), and Desanker and Reed (1993), this is at least partly because $H_{\max}$ and $D_{\max}$ are site specific. Ek et al. (1984) gave an expression relating total tree height to DBH, site index, and stand basal area for each of the four species in this study. By using the observed site indices from the study plots and assuming an asymptotic stand basal area, the equations given by Ek et al. (1984) were utilized to estimate $D_{\max}$ and $H_{\max}$ for the study plots. An asymptotic basal area of 32 m^2 ha^{-1} was chosen; basal areas exceeding this in mixed species stands of this type are possible on small plots, but very rare on the stand level. The final estimates of $D_{\max}$ and $H_{\max}$ are not sensitive to small changes in the selected asymptotic basal areas but can change dramatically when unrealistically high or low asymptotic basal areas are selected. Numerical procedures were used to solve the equations to find the diameter which would lead to insignificant (<0.01 m) height growth; that diameter was taken as $D_{\max}$ for the site and the corresponding height was taken as $H_{\max}$. The resulting estimates of $D_{\max}$ and $H_{\max}$ were used to fix b_2 and b_3 in the model as defined in the limiting relationships given above (Table 2).

Botkin et al. (1972) set G to produce approximately two-thirds of the maximum diameter at one-half of the maximum age. In this study, G was statistically estimated using non-linear regression techniques (Table 2). For paper birch and aspen, asymptotic 99% confidence intervals around the estimated values of G included the values used by Botkin et al. (1972) and Shugart and

West (1977) for these species. For red maple and northern red oak, this was not the case. The value of G incorporates various proportional relationships between total tree biomass increment, leaf area, and leaf biomass (Botkin et al., 1972). Therefore, it is not surprising that site-specific values may be required for some species.

Intertree competition

In the formulation of Botkin et al. (1972), and in following revisions by Shugart and West (1977) and others, the effect of intertree competition on diameter growth is represented in two ways. The first is through a model component representing light availability, which is based on tree height, the height of all other trees in the stand, and shade tolerance (two tolerance classes were used). The second is through a factor representing competition for moisture and nutrients which is simply a ratio of basal area for the stand to maximum stand basal area expected for the cover type.

On these study sites, Holmes (1988) did not find a significant ($P>0.05$) relationship between plot basal area and individual tree diameter growth. The comparison of the height of an individual tree to all other trees on a plot was also judged to be inappropriate, especially since these study plots measure 30 m × 35 m and contain trees which are not measurably affecting each other.

Holmes and Reed (1991) used map information from the study plots to evaluate the performance of numerous individual tree competition indices for each of the four species. The competition indices used here are not necessarily those that were most highly correlated with individual tree diameter growth but they do perform well in the modeling efforts, especially in the combined model when other environmental factors are considered. A simple competition index given by Lorimer (1983) performed well for northern red oak, paper birch, and red maple. This index is given by

$$\mathrm{CI}_i = \sum (\mathrm{DBH}_j/\mathrm{DBH}_i) \tag{5}$$

where CI_i is the value of the competition index for the ith (subject) tree, DBH_i is the diameter of the subject tree, DBH_j is the diameter of the jth competitor, and the summation is over all trees within 7.62 m of the subject tree. Holmes and Reed (1991) found that the relationship between Lorimer's competition index and diameter growth did not differ between sites or across years (1985–1987) for northern red oak, paper birch, and red maple.

For aspen, the least shade tolerant of the four species in this study, the competition index given by Bella (1971) proved to be highly related to observed diameter growth. This index includes additional information regarding the distance to neighboring trees

$$\mathrm{CI}_i = \sum \left[(a_{ij}/A_i) \times (\mathrm{DBH}_j/\mathrm{DBH}_i)^3 \right] \tag{6}$$

where CI_i is the value of the competition index for the ith (subject) tree. DBH_i is the diameter of the subject tree. DBH_j is the diameter of the jth competitor. A_i is the area of the influence zone (as defined by the open grown crown radius given by Ek (1974)) of the ith tree, and a_{ij} is the area of the overlap of the influence zones of the ith tree and the jth competitor. As with Lorimer's index and the other three species, the relationship between Bella's index and aspen diameter growth did not differ between sites or across years (1985–1987).

A negative exponential relationship was assumed between diameter growth and increasing competition. In the diameter growth model, this is represented by

$$IC = e^{-(a \times CI)} \tag{7}$$

where IC is the intertree competition component of the diameter growth model, a is the coefficient to be estimated for each species, and CI is the value of the competition index for the respective tree. There were no significant differences between sites in the estimated value of a (Table 2).

Site physical, chemical, and climatic factors

For environmental factors such as moisture, temperature, and soil nutrient levels, there is expected to be a range of values where a species responds positively to increased amounts of the factor, a range of values where the factor is adequate for the species and there is little response to increases or decreases, and a range of values where the species responds negatively to increased amounts (Spurr and Barnes, 1980; Reed et al., 1990). Reed et al. (1992) describe an intensive variable screening procedure that was used to identify a set of environmental variables for each species which were correlated, either positively or negatively, with diameter growth on the study sites. These variables were selected to be as independent of each other as possible; the environmental factors selected were used in an analysis of covariance and accounted for significant differences in diameter growth between sites and among years.

A component was added to the diameter growth model to represent the effect of site physical, chemical, and climatic factors on growth. The environmental factors were accounted for in the model by a linear function constrained to produce the proportion of potential growth which might be expected

$$SPC = \frac{(DBH + c_0 + c_1 X_1 + c_2 X_2 + c_3 X_3)}{DBH} \tag{8}$$

where SPC is the effect of physical, chemical, and climatic factors on diameter growth and DBH is tree diameter. The particular environmental factors

(X_k) and the associated constants (c_k) are species specific. The factors identified in this study were total seasonal air temperature growing degree days (April–September) on a 4.4°C basis for northern red oak, paper birch, and aspen, and air temperature degree days through May for red maple, July soil potassium concentration (p.p.m.) in the upper 15 cm of mineral soil for aspen and red maple, and soil water holding capacity (cm/cm) at a depth of 5–10 cm for red maple and at a depth of 10–30 cm for paper birch. The intercept (c_0) was not significant ($P>0.05$) for northern red oak and paper birch and was removed from the model for these two species (Table 2).

Seasonal growth pattern and effect of weekly climatic conditions

Fuller et al. (1987) found that cumulative total air temperature degree days (4.4°C basis) was the most significant environmental factor impacting the timing of diameter growth for all four species on both sites. Reed et al. (1990) modeled the proportion of annual growth expected in a given week using a difference form of a modified Chapman–Richards growth function and the cumulative air temperature degree days at the beginning and end of the week. This requires the implicit assumption that each species will respond to temperature up to a point and that further increases in degree days will not lead to increased growth.

Increased air temperature leads to increased plant respiration and evaporation which may result in decreased levels of soil moisture. The expected growth, given the cumulative air temperature degree days, will not be achieved if moisture is limiting. In the model, average soil water potential (−MPa) at a depth of 5 cm is used to indicate the level of moisture stress. At a value of water potential less than 0.101 −MPa, water is freely available to plants and is not assumed to be limiting. At potentials greater than 0.101 −MPa, moisture may limit growth to some extent; plant response is assumed to be a simple exponential function of increasing soil water potential. If the observed average soil water potential for a week is less than 0.101 −MPa, a value of 0.101 −MPa was used in the estimation procedure.

The model component representing weekly growth combines the effects of cumulative air temperature degree days at the beginning (ATD_{t_1}) and end (ATD_{t_2}) of week t and average soil water potential at 5 cm in week t (SWP_t)

$$\mathrm{SGP}_t = [e^{-(\mathrm{ATD}_{t_1}/d_1)^{d_2}} - e^{-(\mathrm{ATD}_{t_2}/d_1)^{d_2}}] \times [e^{-d_3(\mathrm{SWP}_t - 0.101)}] \qquad (9)$$

where SGP_t is the proportion of potential total annual growth expected in week t. The coefficients d_1, d_2, and d_3 are species-specific coefficients and are estimated statistically using non-linear regression techniques (Table 2).

Combined model

The combined model, incorporating all four model components discussed

above, was fitted to data from both sites for the 1986 and 1987 growing seasons. This allowed the examination of site differences in the coefficients due to tree and climatic differences in the 1986 and 1987 growing seasons. There were no differences in any coefficient by site so the data were combined to estimate the coefficients for each species. Data from the 1988 growing season were used for testing, but were not used in estimating the coefficients. Predictions of total seasonal diameter growth were made for each tree and compared with the observed growth values. A studentized test on the average residual found no evidence of bias in the combined model for any species except for aspen (Table 3). In other words, the average residual was not different from zero ($P>0.10$) for northern red oak, paper birch, and red maple. For aspen, the average residual was different from zero ($P=0.01$), indicating a significant underprediction of observed growth by the combined model. This result is probably a consequence of a number of factors, including the small sample size for aspen, the extreme genetic diversity found in aspen in the Lake States, and the clonal growth of aspen (Fowells, 1965).

The standard error of the residuals in the estimation data is analogous to the square root of the mean squared error in ordinary linear regression. The standard error of the residuals in the estimation data set is less than the measurement increment (0.008 cm) for all species except aspen (Table 3). This implies that the model prediction is within the measurement precision for those species and further improvement is unlikely.

The proportion of variation explained in total annual diameter growth

TABLE 3

Diameter growth model performance for each species when predicting total seasonal growth (sites and years combined)

Species	Proportion of variation explained[1]	Average residual (cm)	Standard error of residuals (cm)	$H_0: \mu_R=0$ $H_a: \mu_R\neq 0$
Northern red oak	0.443	0.0128 (6.4%)	0.0079	NS
Paper birch	0.724	0.0037 (6.1%)	0.0075	NS
Aspen	0.286	0.0328 (16.9%)	0.0105	$P=0.01$
Red maple	0.512	0.0010 (1.0%)	0.0041	NS

[1]Proportion of variation explained is calculated as follows

$$\mathrm{PVE}=\frac{\sum(Y_i-\bar{Y})^2-\sum(Y_i-\hat{Y}_i)^2}{\sum(Y_i-\bar{Y})^2}$$

where Y_i is the observed growth for the ith tree; $\hat{Y}_i$ is the predicted growth for the ith tree; $\bar{Y}$ is the average growth for all trees of the same species as the ith tree.

(Table 3) is analogous to R^2 in linear regression, and for all four species is in the range found by other studies in deciduous species (e.g. Harrison et al., 1986). Further improvement in these values may not be possible at the study sites because of the precision of the field measurements and the rates of observed growth.

Residual analysis

The analysis of the model's ability to predict growth is divided into two components: total annual growth and seasonal pattern of growth. The predicted total annual growth is obtained by summing the weekly growth predictions over the entire growing season. The predicted seasonal growth pattern is determined by the cumulative growth to any given week during the growing season.

Total annual growth

Annual residuals, by site, are given for each species in Table 4. These comparisons involve the sum of the predicted weekly diameter growth over a season compared with the total observed growth during the season. As mentioned previously, the data from 1986 and 1987 were used in model estimation; the data from 1988 were not used in estimation. The 1988 comparisons between the observed and predicted values can, in some ways, be interpreted as a test of the model under new conditions. While the same trees measured in previous years are remeasured, the particular combination of weather conditions in 1988 are unique. Thus, while not being an independent test of the model, the 1988 comparisons can provide insight into model performance under conditions other than those in the estimation data set.

As seen in Table 4, for northern red oak and paper birch, the studentized 95% confidence limits for each of the 3 years on both sites include zero, indicating no significant deviation in growth from that predicted by the model. For red maple, the studentized 95% confidence intervals for both sites in 1986 and 1987 include zero, indicating unbiased model predictions during the years from which the estimation data were obtained. In 1988, there was a large negative residual at each site, and the residuals were not different between sites. This indicates that the model did not adequately represent the growing conditions in 1988 and that some factor or combination of factors led to a reduced average diameter growth rate for red maple which was not seen in previous years but which was apparent at both sites.

In searching for differences in environmental factors between 1988 and previous years, the major difference appears to be related to moisture. Average air temperature at 2 m above the ground and average precipitation are not significantly different between years (Table 5), but relative humidity and soil water potential at 5 cm were significantly different in 1988 than in pre-

TABLE 4

Performance of the diameter growth model in predicting total seasonal growth by site and year for each species

Site	Year	Number of observations	Average residual (cm)	Standard error of residuals (cm)	Studentized 95% confidence interval
Northern red oak					
1	1986	61	−0.0069	0.0103	−0.0275, 0.0137
	1987	62	0.0135	0.0112	−0.0089, 0.0359
	1988	62	−0.0178	0.0113	−0.0414, 0.0048
2	1986	20	0.0204	0.0251	−0.0321, 0.0776
	1987	22	0.0797	0.0323	−0.0125, 0.1469
	1988	23	0.0250	0.0202	−0.0169, 0.0669
Paper birch					
1	1986	10	0.0047	0.0162	−0.0139, 0.0413
	1987	10	0.0007	0.0086	−0.0188, 0.0202
	1988	10	0.0270	0.0270	−0.0200, 0.0740
2	1986	3	0.0191	0.0241	−0.0846, 0.1228
	1987	3	−0.0083	0.0153	−0.0711, 0.0605
	1988	3	−0.0048	0.0207	−0.0939, 0.0843
Aspen					
1	1986	30	0.0033	0.0222	0.0079, 0.0987
	1987	29	0.0032	0.0133	−0.0240, 0.0304
	1988	28	0.0533	0.0184	−0.0048, 0.0411
2	1986	11	0.0282	0.0193	−0.0143, 0.0707
	1987	11	0.0599	0.0227	0.0099, 0.1099
	1988	10	0.1175	0.0175	0.0779, 0.1571
Red maple					
1	1986	10	0.0307	0.0143	−0.0016, 0.0630
	1987	10	0.0095	0.0129	−0.0197, 0.0387
	1988	10	−0.0852	0.0243	−0.1402, −0.0302
2	1986	70	−0.0019	0.0059	−0.0136, 0.0098
	1987	80	0.0002	0.0064	−0.0125, 0.0129
	1988	84	−0.0771	0.0053	−0.0876, −0.0666

vious years. This indicates the possibility of increased moisture stress in 1988. Red maple is a widespread tree species found on many types of sites; it is characteristic of bottomland, swampy, and moist sites but it often occurs under drier conditions (Fowells, 1965; Harlow and Harrar, 1969). Reduced moisture availability on the study sites in 1988, as indicated by soil water

TABLE 5

Average April–October weather conditions on the two study sites

Variable	Site	Year 1986	1987	1988
Air temperature (°C 2 m aboveground)	1	12.9	13.5	13.3
	2	12.0	12.7	12.5
Soil temperature (°C at 5 cm depth)	1	11.7	12.3	11.6
	2	11.2	11.8	11.2
Precipitation (cm)	1	36.6	53.4	44.7
	2	34.2	56.1	53.1
Relative humidity (%)	1	–	70.0	62.5
	2	–	84.1	80.1
Soil moisture (% at 5 cm)	1	14.1	10.9	10.6
	2	10.4	10.8	9.5

potential at 5 cm, could be the cause of the reduced growth compared with previous years. This emphasizes the necessity of data collection over a longer time period in order to fully evaluate the effect of climatic conditions on tree growth.

Aspen is the only species for which there is a mixed response between the two sites (Table 4). The residuals of total annual aspen diameter growth at Site 1 have increased over the 3 year study period while they have remained relatively constant at Site 2. Both sites are located adjacent to a cleared area but the average distance from the edge to the individual aspen trees is roughly equal for the two sites. In addition, there is no difference in crown position between individuals at both sites; the aspen individuals in these mixed stands all tend to be dominant or codominant individuals. There was also no significant difference in total leaf biomass produced at Site 1 between 1988 and previous years. Taken together, these factors indicate that the aspen at Site 1 could not be responding to an increased light environment in 1988. There is a greater red maple component at Site 1 than at Site 2, and the aspen could be responding to reduced competition from red maple because of the reduction in red maple growth described above. If so, this is happening at Site 1 and not at Site 2 and it is happening in the absence of increased light.

To summarize the total annual growth comparisons, the model performed well for two species (northern red oak and paper birch) at both sites for all 3

years. For one species (red maple), the model did not perform well in 1988 at either site. It is possible that this is a result of decreased moisture availability compared with previous years. These results emphasize the fact that each year represents a unique combination of environmental conditions, and an extended sampling period is needed to fully understand the relationships between tree productivity and climate. For the fourth species (aspen), there is a divergence in model performance between the two sites. The cause of this is not obvious at this time but there does not appear to be a simple environmental or competitive explanation based on the available information from the sites.

Seasonal growth pattern

Seasonal growth pattern is driven in the model by cumulative air temperature degree days and soil water potential on a weekly basis. Differences between estimated and observed seasonal growth patterns are examined using the Kolmogorov–Smirnov procedure to compare the observed and predicted cumulative growth percentages for each week. If an environmental variable affecting seasonal growth pattern is not included in the model, the observed pattern should differ from the predicted pattern. An illustration of the observed and predicted growth pattern is given in Fig. 1.

For northern red oak, there were no significant differences ($P > 0.05$) between the observed and predicted seasonal diameter growth patterns at either site in any of the 3 years. This indicates that there is no significant deviation from the seasonal diameter growth pattern predicted by the model.

Fig. 1. Observed and predicted seasonal growth patterns for northern red oak on Plot 2, Site 2 in 1988.

For paper birch at Site 1, there were no significant differences between the observed and predicted seasonal growth pattern in any of the 3 years. At Site 2, there were significant differences ($P < 0.05$) between the observed and predicted seasonal growth patterns on one plot in all 3 years and in a second plot in 1987 and 1988; there were no differences on the third plot. It is not clear that these differences are the result of any seasonal difference in climatic conditions between the two sites. The overall effect was that the model predicted a lower proportion of growth early in the year compared with what was observed. As discussed earlier, the overall net effect did not include a difference in total annual growth. The differences may largely be a consequence of small numbers of trees being included in the plot level comparisons.

There were no significant differences ($P > 0.05$) between the observed and predicted seasonal growth patterns for red maple at Site 1 with the exception of one plot in 1986 and another plot in 1988. At Site 2, there was a significant difference ($P < 0.05$) on one plot in 1988 but not in 1986 or 1987 and no differences for the other two plots. There does not seem to be any pattern to these differences. For the majority of plots and years there was no difference between the observed and predicted seasonal growth patterns.

For aspen, there was a significant difference ($P < 0.05$) between the observed and predicted seasonal growth pattern for only one plot in 1 year (1988) at Site 1. This plot only contains a single aspen individual and, while this difference could be related to the increased aspen growth at Site 1, unless this difference is repeated in the future and found on other plots at Site 1 there is no real evidence of a systematic inadequacy in the model's prediction of seasonal diameter growth pattern. At Site 2, there were no differences ($P < 0.05$) between observed and predicted aspen seasonal growth pattern with the exception of one plot in 1986. In 1986, the studentized 95% confidence intervals for the total annual growth residuals did not include zero and this may be having an influence on the evaluation of seasonal growth pattern. This difference was not repeated in later years and, since it only occurred on one plot, does not seem to indicate a serious problem with the model.

In the seasonal growth pattern evaluations, comparisons were made on a plot basis (using the three plots at each site) rather than on the site level. There were a number of instances where individual plots differed in observed and predicted seasonal growth pattern for single years, but paper birch at Site 2 was the only case where differences between the observed and predicted patterns were noted on all or most of the plots. Even here, there were no apparent climatic differences which seemed to have caused the model performance to deteriorate. Whatever the cause, it was not sufficient to be associated with an overall decrease of model performance in estimating total annual growth as discussed above.

CONCLUSIONS

Many existing models which represent tree growth as a response to climate contain assumptions which may be adequate on a regional basis but which cause poor model performance on many individual sites. Species' maximum diameters and heights, for example, are utilized in many of these models and, while it is well known that these are site dependent, this fact is not recognized in most existing growth models. Another example is a species' response to climate. From provenance trials it is well known for many species that genetic material from different locations within a species' geographic range responds differently to climatic conditions at a given site (Carter, 1991). In many existing models a species' growth response to a given heat sum is assumed to be constant, even though differences in heat sum are used to represent different sites. There are many problems, therefore, in utilizing existing models to project the response of local tree populations and ecosystems to changing environmental conditions.

For many species and localities, traditional forest growth and yield information can be utilized in localizing the dimensional limits in existing models. Because of the problems encountered when applying existing models to local populations, it is important to localize such models when applying them to historical data to investigate impacts of historical climatic or pollutant exposure conditions. In this study, methods were developed and illustrated which utilize height/diameter models from the literature to develop expressions for maximum tree height and diameter as a function of site index and maximum stand basal area. Such methods of localizing existing growth models could be developed for many species in much of the world.

An annual timestep may not be sufficient for modeling tree response to environmental conditions. Ecosystem level response to a shift in environmental conditions may be on the order of several years while an individual tree's response to changes in environmental conditions, such as moisture or nutritional status, is on the order of a few days. Also, the timing of events such as drought during the growing season is as critical as their intensity in determining their effect on tree growth. The amounts and timing of precipitation and the temperature pattern within a given year interact to make each year a unique combination of environmental factors affecting plant communities. For these reasons, a weekly timestep was utilized in modeling seasonal growth pattern and, by summation, total annual diameter growth on the study sites.

In this study, over two sites and 3 years, the model of seasonal and annual diameter growth performed well for two of the four species. For a third species, there was a growth reduction at both sites in the third year, most likely a result of a combination of temperature and precipitation leading to a reduction in available water during the growing season. For the fourth species, there

was an unexplained differential in model performance between the two sites. These results emphasize the need for site-specific information collected annually over an extended period in order to fully understand and quantify the effects of environmental factors on forest productivity.

ACKNOWLEDGMENTS

This study was funded by the US Navy Space and Naval Warfare Systems Command through a subcontract with the Illinois Institute of Technology Research Institute under contract number E06595-84-C-001.

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Appendix G

ANOVA design used for analysis of each individual macronutrient concentration.

Source of Variation	D.F.	M.S.	F-Test
Site (S)	2	MSS	MSS/MSE P(S)
Error Plot within Site	(P(S))	3(2) MSE P(S)	
Years (Y)	# Years-1	MSY	MSY/MSE YxP(S)
Site x Years (SxY)	(2)(Years-1)	MSSxY	MSSxY/MSE YxP(S)
Error YxP(S)	(Years-1)3(2)	MSYxP(S)	